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Low Weight Design Of A Pressure-Fed System For A Small Payload Launch Vehicle

Lucero Buendia

University of Texas at El Paso

LOW WEIGHT DESIGN OF A PRESSURE-FED SYSTEM FOR A SMALL PAYLOAD LAUNCH VEHICLE

LUCERO BUENDIA

Master's Program in Mechanical Engineering

APPROVED:

____
Alejandra Castellanos, Ph.D., Chair

____
Jack Chessa, Ph.D.

____
Cesar Carrasco, Ph.D.

____
Stephen L. Crites, Ph.D.
Dean of the Graduate School

To My

Family and Many Friends;

You Mean the World to Me

LOW WEIGHT DESIGN OF A PRESSURE-FED SYSTEM FOR A SMALL PAYLOAD LAUNCH VEHICLE

by

LUCERO BUENDIA

THESIS

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Abstract

Carbon fiber reinforced polymer (CFRP) composites have become of great interests to aerospace industries because of their low-cost, lightweight and their tailorable mechanical properties. In aerospace structures, for example, heavy metals have been used in cryogenic fuel and oxidizer tanks for over 50 years. However, weight savings can be substantial if materials such as composites are used instead. From Delta IV heavy-lift launch vehicle it is known that cryogenic composite tanks can save approximately up to 30% of weight in fuel and oxidizer tanks. Although there is a wealth of studies in the mechanical behavior of composites at room temperature, very few work has been reported at cryogenic temperatures. The lack of research information concerning composite materials behavior at cryogenic temperatures (-253 ℃) is often the cause that holds back engineers from incorporating them in aerospace structures for safety reasons. The University of Texas at El Paso designed a launch vehicle to operate with liner-less pressure-fed common bulkhead carbon fiber cryogenic tanks. The pressure fed system will allow for scalability and engine capabilities adaptation so that the cryogenic tanks can be used in a transfer stage or lunar lander. However, it is still unknown what fiber and epoxy matrix and layup will make it scientifically reasonable and feasible. Finite element analysis has been done on tanks but there is a need to better understand the materials at cryogenic temperatures. The purpose of this project is to study the tensile behavior of carbon fiber/epoxy and Kevlar/epoxy composites at 25 ℃, -60 ℃ and thermal gradient temperature of 25 ℃/ -60 ℃. Mechanical properties obtained will prove the potential of textile composites to manufacture cryogenic propellant tanks.

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Chapter 1

Introduction

With NASA's current mission to land the first women and next men on the moon by 2024, launch vehicles play a significant role in making it possible. Whether it is as a shared ride, as a primary or secondary payload, launch vehicles can be used to transport an object into an orbital outside or within Earth's atmosphere. Therefore, it is crucial that their components are of low-weight and resistant to space cold temperatures while ensuring the crew safety and mission success.

A launch vehicle is composed of multiple parts, among them fuel and oxidizer tanks, which tempt to be the heaviest dry mass. For many years metal tanks have been used to store a launch vehicle fuel and an oxidizer at cryogenic temperatures (-253 ℃ and -183 ℃)[1]. 2000 series of aluminum alloys are commonly used due to its resistance to cryogenic temperatures, prevent gas permeability and can withstand high launch loads of aerodynamic pressures. In the last decade, aerospace companies have been looking for alternative materials that can help make a successful low-cost, low weight yet efficient and reliable vehicle. Carbon fiber/polymer matrix composites have become an attractive solution for this challenge, as they can help reduce the total weight of the tank by up to 30% as compared to conventional tanks made of metals [2]. Cryogenic propellant tanks made from carbon composite materials are also a very appealing candidate to handle the thermogradient temperature in cryogenic tanks, high stiffness-to-weight ratio, design flexibility and higher strength than heavy conventional materials such as steel and aluminum.

UTEP's cSETR preliminary launch vehicle design incorporates as many carbon composite materials within its structural design, including the propellant tanks. It is also the intent of this launch vehicle to operate with a pressure fed system as the propulsion system. It has been calculated that a 2 $\frac{1}{2}$ stage launch vehicle with a mission to Low Earth Orbit (LEO) with a height of 60 ft and a mass 25, 305 lb. can allow for the innovative idea of a pressure-fed carbon composite launch vehicle. Through the use of a linerless common bulkhead core stage tank that operates on Methane/ Liquid Oxygen (CH_4/LOX), weight reductions will support a successful lift. Launch vehicles are at risk of not lifting-off when mass budgets are not met resulting in a failed mission.

The launch vehicle will consist of four solid rocket boosters, core stage, and upper stage. This thesis project will focus in the study of carbon composite materials for the application of cryogenic propellant tanks.

What makes carbon composite cryogenic tanks so appealing is their potential ability to withstand the thermogradient temperature that exists when exposed to liquid methane and/or liquid oxygen. This paper will focus on investigating the mechanical properties of a selective carbon composite material system to determine its potential applications in a launch vehicle through a novel research procedure. First, the benefits of incorporating materials like these in an innovative launch vehicle will be discussed.

Pressure-fed Systems

Pump-fed systems are typically used for the thrust output they can provide using less fuel and oxidizer quantities. The correlation between the thrust and the weight of the vehicle is key to mission success. If the launch vehicle surpasses the amount of thrust generated there will be no lift-off. The heavier the vehicle, the higher the thrust required, the lighter the payload mass is allowable. For pump-fed systems to output the required thrust to lift-off a higher amount of fuel and oxidizer is required compared to pump-fed. The byproduct is bigger propellant tanks, thus heavier launch vehicles. However, if cryogenic propellant tanks are incorporated the weight reductions can easily accommodate a pressure-fed system. The main reason why UTEP's cSETR is pushing for a pressure-fed system as the main propulsion source throughout the launch vehicle is mainly because of its simplicity, due to the fact that it only requires a pressure source, low-cost, space propulsion applications, and easy scalability according to the mission. Having that said, Helium will be used to serve as the pressure source to feed oxidizer and fuel to the engine. Helium quantity varies depending on the mission and firing location. Thus, mass budgets must account for the mass of the pressurant tank and mass of the Helium. When considering CH_4/LOX as the operating fuel and oxidizer for a launch vehicle, a pressure-fed system would be optimal in order to meet the mass to fuel ratio. A core stage operating on pressure-fed engines with traditional metal propellant tanks are not realistic and certainly not going anywhere because of how heavy it will be. If cryogenic carbon composite tanks are used instead the stage gross mass would be 12,193 lbm, with an inert mass fraction of 0.17 and can be successful using 10,120 lb. of CH_4/LOX with one pump-fed engine that will provide 12,000 lb. of thrust.

Linerless Tank

The core stage tank will be the biggest and thus heaviest component of the launch vehicle. Manufacturing this cryogenic tank from carbon composite materials can result in weight reductions without jeopardizing mission success. There exist different types of pressure vessels. Cryogenic composite tanks that have flow are either type III which means the tank has a metal liner and it is partially over wrap. In some cases, the tank has a polymer liner and it is composite-overwrapped, also known as type IV[3]. The proposed launch vehicle design will consist of an all-composite tank without a liner. Further weight reductions can be achieved by using a type V composite because the liners weight won't have to be taken account for.

Launch vehicles with carbon composite tanks use a liner to prevent leaks from micro-cracks that might develop in the carbon fiber tanks. In 2006 the Air Force Research Laboratory (AFRL/ VSSV) and Composite Technology Development (CTD) Inc. worked together to develop a toughened matrix. They investigated the formation of micro-cracks and the porosity of the laminates to improve the design of linerless composite tanks. CTD modified epoxy resins using polymers, copolymer impact modifiers and vapor grown fiber (VGCF) nano-reinforcement to create six innovative epoxies. They studied the micro-cracking fracture toughness of the epoxies. Results showed that two of their modified epoxies (CTD-7.1 and CTD-DP5.1) had a higher micro-crack fracture toughness than commercially off the shelf resins and 1 % delamination strain higher. They also proposed that an iso-strain dome can make a common bulkhead more efficient and account for transverse loads.[4]

Thus, it is crucial to pick a material system capable of withstanding high aerodynamic loads, contain gas permeability, reduce crack propagation, and most importantly hold out against the cryogenic temperatures of oxidizer and fuel.

Common-bulkhead Tank

In addition, carbon composite tanks design can be manipulated to be a common-bulkhead tank. Common-bulkhead tanks are essentially just a combination of propellant tanks (fuel and oxidizer) as one tank, where each has their own volumetric space but is divided by domes also known as common-bulkheads. For example, a cryogenic oxidizer and fuel tank can be combined as one tank and share one common-bulkhead. In the case of a pressure-fed system, a helium tank, cryogenic fuel and oxidizer tanks can be combined through two common-bulkheads. Common-bulkhead tanks not only save space but also reduce the weight of launch vehicles.

However, a launch vehicle with linerless common-bulkhead carbon composite tanks has not been done yet. It has been attempted by several companies in the early 1980s but due to their unsuccessful outcomes funding was cancelled and projects were abandoned. The Big Dumb Booster, for example, was being designed to use a pressure-fed propulsion system and had ground tests funded by the air force in the late 1960s, but the project was unfortunately stopped to allocate funding to a reusable space shuttle before a complete prototype could be tested.[5]

In conclusion, carbon composite tanks must be capable of handling loads at lift-off (pressure, tension, compression and/or shear), mass of stages and payload above (if any), mass of its respective fuel/oxidizer/helium content, and most important the drastic temperature changes from room temperature to cryogenic temperatures to avoid catastrophes. The intent of this project is to prove how carbon composites will make the idea of a pressure-fed liner-less common bulkhead carbon composite for a launch vehicle feasible. First a material system will be chosen based on literature review, samples will be manufactured, waterjet cut, conditioned and finally, tensile testing.

Understanding the behavior of polymer matrix composites at cryogenic temperatures is critical for the survival of cryogenic propellant tanks. In the current study, the mechanical response and damage mechanisms of woven carbon/epoxy and Kevlar/epoxy composites subjected to extreme thermal gradient is investigated.

Chapter 2

Literature Review

2.1 Cryogenic Composite Tanks in History

There has been a great interest in carbon composite cryogenic tanks since the early 1970s. However, it wasn't until the 1980s that projects started to get funded to manufacture and test cryogenic tanks. There was a vast variety of projects that were picked up by different organizations but were renamed and thus those are commonly heard of. Others failed to pass ground testing, but lessons learned were applied to a different project with a different mission.

DC - XA liquid hydrogen cryogenic tank (Fig. 1), for example, was a project that started with the intent of replacing aluminum tanks in order to meet requirements. The tank was manufactured in two halves using carbon/epoxy (IM7/8552) prepreg material and was insulated on the inside as Saturn S-IVB design. It was the first cryogenic composite tank to successfully fly four times before the program was cancelled shortly after the Delta Clipper was damaged[6][7].

Figure 1: DC - XA Zheng, Hongfei. "DC-XA composite LH2 cryotank." Intech Open, 14 March 2018, https://www.intechopen.com/books/solidification/the-application-of-carbon-fiber-composites-in-cryotank

X-33 (Fig. 2) is another project aiming to design a cryogenic composite tank. It also used carbon/epoxy prepreg material (IM7/977-2) but unlike DC-XA, this tank incorporated a KorexTM+3-pcf honeycomb multi bonded structure. X-33 design was considered novel although issues arise due to the adhesion tank wall on the honeycomb. This cryogenic tank unfortunately failed due to microcracking from LH2 leakage and outer skin delamination from the honeycomb. Program was then cancelled but tank failure wasn't the main cause[6][7].

Figure 2: X - 33 Douglas, McCarville. "X-33 composite liquid hydrogen (LH2) tank failure" NASA Technical Reports Server, 28 Aug. 2017, https://ntrs.nasa.gov/search.jsp?R=20170012407

Space Launch Initiative Composite Cryotank Program ([6][7]) ((Fig. 3)) was created with the intent to take the lessons learned from X-33 and apply them to design a cryogenic tank that will reduce microcracking and permeability. A carbon composite honeycomb structure was incorporated with an aluminum foil liner to prevent liquid hydrogen from leaking. Thin prepreg carbon composite skins in the honeycomb reduce microcracking by a factor of 16. Unlike DC-XA and X-33, this project opted to use novel ultrasonic tape lamination approach rather than expensive autoclave. The project concluded that carbon composite materials have the necessary mechanical and thermal properties to withstand cryogenic fueling and stresses experienced in a typical reusable launch vehicle cryotank.

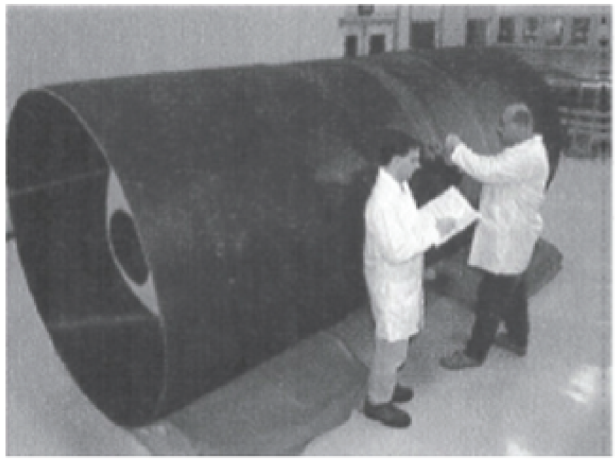

Figure 3: Space Launch Initiative Composite Cryotank Zheng, Hongfei. "DC-XA composite LH2 cryotank." Intech Open, 14 March 2018, https://www.intechopen.com/books/solidification/the-application-of-carbon-fiber-composites-in-cryotank

Composite Cryogenic Technology Demonstration Project (CCTD)([6][7]) ((Fig. 4)) was a project with the intent to manufacture a cryogenic tank without expensive autoclave machines and use vacuum-assisted resin transfer molding (VARTM) process instead. The main goal was to reduce the weight of a typical metal cryogenic tank by 30 % and reduce cost by 20- 25 %. It was a team effort of multiple aerospace companies such as NASA, Lockheed, Boeing and Northrop Grumman where they each contributed a concept to compare cost saving and findings. It was discovered that cost savings can be achieved using carbon composites. Also, that a toughened epoxy prepreg resin cured through vacuum-bag-only curing is just as efficient as autoclave curing and it can even result in less porosity and superior mechanical properties. It was also found that a combination of thick and thin plies (12 and 5 plies respectively) reduced crack propagation and permeation allowing tanks to meet requirements without hesitation. It is also important to mention that the prototype tanks were unidirectional and manufactured through automated fiber placement. Also, the tank required mandrels and was manufactured in halves and cured separately before being attached through fasteners.

Figure 4: CCTD Zheng, Hongfei. "DC-XA composite LH2 cryotank." Intech Open, 14 March 2018, https://www.intechopen.com/books/solidification/the-application-of-carbon-fiber-composites-in-cryotank

2.2 Material System Literature Review

The in-plane mechanical properties of polymer matrix composites are very stiff and strong. However, the transverse properties, which are matrix dominated are very weak. There is plenty of study on the mechanical behavior of polymer matrix composites at room temperature. However, there is very little work on the mechanical behavior of composites when exposed to cryogenic environments.

The lack of knowledge on its behavior when exposed to any of the cryogenic environments makes it challenging to design components that will properly respond when subjected to load (tension, compression, shear). There are a lot of components that contribute to picking the appropriate material system that make a resistant carbon composite tank. Factors can include but not be limited to density of matrix, matrix type, type of carbon fabric, resin mechanical properties, ultimate tensile strength at cryogenic temperatures of composite, ultimate tensile strength after conditioning of composite, crack propagation, gas permeability, and young's modulus.

2.2.1 Carbon / Epoxy

Aoki et al. ([8]) studied the mechanical behavior of unidirectional carbon fiber (CF)/epoxy, CF/bismaleimide and CF/Polyether ether ketone (PEEK) composites. The in-situ tensile behavior and interlaminar fracture toughness at cryogenic temperatures (-196 ℃ and -296 ℃) were investigated. They concluded that the Young's modulus was less susceptible to temperature change, the tensile strength reduced up to 80 %, the fracture toughness increased and matrix cracks were the main failure mechanism at cryogenic temperatures.

Whitley et al. ([9]) studied the cryogenic temperatures in polymer matrix composites (PMC's) under tensile loads and determined if it's an adequate structural material for cryotanks. Tension testing was conducted at three different temperatures (25 ℃, -196 ℃ and -296 ℃). Preconditioned aging (-184 ℃ for 576 hours) was done on samples prior to testing. It was concluded that longitudinal stiffness, transverse stiffness and strength decrease as temperature decreases when in tension. There was an increase in tensile strength and stiffness in samples that were isothermally cryogenic aged. However, higher stresses and lowest strength were found in samples aged tested at -196 ℃.

Gates et al. ([10]) studied the influence of temperature, aging and loading pose on 5 different ply layups of polymeric-matrix composite (PMC) material coupons. Pure tension testing was conducted at 3 different temperatures (25 ℃, -196 ℃ and -269 ℃) along with preconditioned (unloaded isothermally aged, constant strain, mechanically cycled) at -184 ℃ for 576 hours. It was concluded that stiffness and strength is affected by the change in temperature and loading conditions, but there is no linear correlation. Lastly, mechanical properties are affected by preconditioning specimens during a prolonged period at cryogenic temperatures.

In the work by Namata et al. ([11]) carbon fiber reinforced epoxy composites (CFRPs) samples underwent tension testing at two different temperatures (25 ℃ and -196 ℃). The effects on the amount of carbon fiber and softener content in epoxy were studied. Samples were submerged in liquid nitrogen while tension testing was conducted. Results stated that softener improved tensile properties of samples at -196 ℃. Tensile strength increased at room temperature when carbon fiber content increased. The Young's modulus increased at cryogenic temperatures when carbon fiber amount increased. In conclusion, carbon fiber with higher Young's modulus had a greater impact than modified epoxy.

Horiuchi et al. ([12]) investigated the effect that carbon-fiber content has on the ultimate strength, the tensile strength and the thermal conductivity of carbon fiber /epoxy composites. Tests were conducted at 4.2 and 77 K. They found out that higher ultimate strength was seen at 77 K, and the tensile strength-to-thermal conductivity ratio was higher as the carbon-fiber concentration increased.

2.2.2 Woven Fabric

Sanchez - Saez et al. ([13]) studied the mechanical behavior on two carbon fiber reinforced/epoxy laminate layups (cross-ply and quasi-isotropic laminates) at 3 different temperatures (20 ℃, -60 ℃, and -150 ℃). The Ultimate tensile strength decreased as temperature decreased for both layups, but the failure strain value of quasi isotropic layup was further affected by low temperatures and higher at 20 ℃. However, the stiffness of quasi isotropic increased as temperature decreased while cross ply (unidirectional) was slightly affected.

Choi et al. ([14]) research focus on the effect cryogenic cycling (300 K to 77 K) on the gas permeability (helium) has on two composite laminas (textile and cross-ply). Tests were conducted at room temperature and results showed textile composites have a lower permeability than cross-ply laminas. Although microcracks developed in textile laminas after thermocycling, the permeability was not affected because these never connect as the damage is constricted by the weave of the fabric. However, well dispersed plies performed well and resulted in less permeability after being cryogenic- thermocycle.

Composite Technology Development Inc. ([3]) is a company that sells all-composite pressure vessels. J. Cronin states in a patent available to the public that the company specializes in Type- V pressure vessels to minimize the weight of the tank. The company achieved a liner less Type V pressure vessel using a highly ductile resin material and woven-fiber-plies. Woven-fiber plies are used to reduce crack propagation, gas permeability, and resin microcracks to prevent failure by leakage or rupture. The patent states that fiber-reinforced-polymer plies are arranged in a way so that the first layer accounts for leakage and/or damage while the rest of the layers provide stiffness and strength. Angles (between 15° and 75°) at which the pressure vessel is braided account for the uniform and non-uniform tension experienced while being internally pressurized. A tria-axial weave is used to adjust the tensile loads experiencing and improve the strength and stiffness. Although no information is given as to the thickness of the tanks, number of woven layers, or resin material properties, CTD states that their tanks are braided in a dissolvable or removable mandrel. A 6 in. dia.x7in. long linerless pressure vessel made from braided plies designed and manufactured by CTS weigh 516 grams. It withstood 5500 psi after being subjected to hydrostatic pressure.

2.2.3 Permeability

In the research of M. Flanagan et al. ([15]) four different carbon fiber polyetheretherketone composites were manufactured in three different methods (autoclave, press and automated tape placement). It was the intent of this research to determine if IM7 and PEEK was suitable for a cryogenic tank based on permeability levels. Samples were tested at room temperature and after cryogenic thermocycling (-196 ℃). Frick's laws of diffusion were used as a guide to dictate the effectiveness of a sample. Results showed that permeability affected all samples cryogenically thermocycle regardless of the manufacturing process. Fickian behavior was seen in CF-PEEK and thus results at room temperatures were stated to be conservative. For a non-Frickain behavior manifestation such as ATP samples, there was a higher leakage rate than those with a Fickian behavior. It was concluded that CF-PEEK is a good candidate for cryotanks for its permeability is low and even the damaged composites did not contribute to the main leakage. However, unidirectional IM7 fiber showed a high leak rate and not suitable for overwrapped pressure vessels.

2.2.4 Resin

Amanda McBride et al. ([16]) studied the effect of hybrid glass and steel reinforcement to determine which one would be more adequate for a structural application. The strength and ductility of 3 different epoxies (EPON 826, EPON 828, and EPIKOTE 874L-X-90) were investigated through tensile testing. Results showed that EPON 828 had the best average tensile strength (7.19 ksi), ultimate tensile strain (2.71 %) and a young's modulus of 381 ksi for epoxy specimens cured at room temperature.

Kim et al. ([17]) compared 6 different epoxy resin compositions in unidirectional CFRP composites. Tensile tests were performed at -150 ℃ after specimens were subjected to thermocycling (6 cycles) from room temperature to -150 ℃. Results showed that resin composition with a high concentration of bisphenol-A epoxy and CTBN had a greater effect on longitudinal tensile strength than it does on longitudinal tensile stiffness. It was also concluded that longitudinal properties are not affected after an abiding exposure to cryogenic temperatures. There is a great benefit from using EPON 828 as a resin that does not entirely need to be defined by its material properties but from resin composition.

Hu et al. ([18]) investigated the mechanical behavior of an epoxy resin (Epon 826) to observe the effect of the deformation response under high stress/ strain range on thin-walled tubular specimens. Specimens were subjected to a combination of internal and external pressures on the walls while axial force (tension) and/or torque was applied at both ends of the tubular specimens. It was found that tensile behaviors correlate more to the Stassi equation than Von Mises with a UTS of 80 MPa. It was concluded that Epon 826 epoxy resin is a nonlinear viscoelastic material and that the deformation response is influenced by the rate of loading and loading path. Hydrostatic pressures up to 17.24 MPa, on the other hand, do not influence the deformation.

Masoud Fard ([19]) investigated the fundamental material properties of polymer resin Epon 863 in tension. Tensile tests were conducted at room temperature and strain was measured using two different methods (digital image correlation (DIC) system extensometer and strain gages. Results showed that Epon 863 has a maximum strain average of 15%. Average elasticity modulus ranged between 2214 to 3081 MPa and average UTS between 71.8 and 81 MPa when using the DIC system. The average elasticity modulus and UTS measured when using strain gages was 2113 MPa and 74.42 MPa respectively. It was concluded that average UTS increases as the strain rate increases. It was also observed that some specimens failed prematurely (4% strain) when using strain gages due to the stress concentration at its respective location.

M. Shokrieh et al. ([20]) investigated the tensile behavior (first ply failure (FPF), final failure (FF), and ultimate strain to failure (USF)) of glass/ epoxy with/or without stress concentration exposed to thermomechanical loading. Tensile tests were conducted at room temperature and -60℃ (using an environmental chamber). Results showed that samples under tensile loads stress-strain behavior was linear elastic until FPF. Strength (347.46 MPa) and stiffness increased as the temperature decreased but the strain to failure decreased. It was concluded that there is a mix mode failure (matrix cracking, fiber breakage, and fiber matrix shearing) at lower temperatures.

Nettles et al. ([21]) studied the properties of carbon-fiber/epoxy (IM7/8551-7) resin systems. Tensile tests were conducted at room temperature, dry ice (CO_2), and cryogenic temperatures (-196 ℃). Results showed that the matrix behavior and deformation mechanisms are a function of temperature. The amount of visual microcracks decreases as the testing temperature decreases and thus it is the reason for nonlinear stress-strain behavior. Matrix toughness also decreased as temperature decreased but specimens tested at lower temperatures were tougher than those tested at room temperature (5.6 GPa vs. 8.1 GPa respectively).

E. Bennett-Huntley ([22]) discussed the benefits of epoxy resin over polyester and vinylester resins. Although epoxy is more expensive versus the other two resin alternatives, its material properties are higher compared to those of polyester which are best suitable for structural applications. Polyester material strength decreases in extreme temperature conditions and fails with time due to its high-water absorption. Polyester might be preferred over vinylester for its fast curing time but vinylester can withstand high vibration loads, output less cracks, resist high impacts and is suitable when working with harsh chemicals. Consequently, vinylester does not easily adhere its own cured resin or to other structures such as carbon fiber and Kevlar. This discards its potential application in composite material designs. Epoxy on the other hand, has superior mechanical properties adequate for structural applications. It is impact resistant, thermo stable and up to three times stronger than vinylester resin. Most importantly, it properly adheres to carbon fiber and Kevlar, provides less permeability and a long-lasting composite that does not lose its structural properties with time.

2.2.5 Kevlar

Fujun Xu et al ([23]). studied the mechanical properties of Kevlar-129 fiber after cryogenically treating the fiber/epoxy samples via two different methods. For comparison purposes, some samples were cooled to 77 K using temperature program-controlled method (TPCM) while others were cooled to 77 K via quenching method (QM) by being submerged to liquid nitrogen. Results showed that tensile strength increases by 24.9% when fiber is conditioned using the QM process while TPCM increases slightly. It was concluded that cryogenic treatment can be used to increase the tensile strength of Kevlar fiber.

Jogi. S. A et al. ([24]) investigated the effect of layup placements (0°/90°, 45°/45°, and 30°/60°) on E-glass/ Kevlar epoxy and E-glass epoxy. Results showed that mechanical properties are affected by the orientation of laminates. Tensile strength and toughness were higher at 0°/90° than angled at 45°/45° and 30°/60° but the deformation percentage was greater. The ultimate tensile strength was higher for E-glass/ Kevlar than E-glass/ epoxy overall. It was concluded that E-glass Kevlar have superior mechanical properties when the orientation of the layup is 0°/90°.

Reddy ([25]) studied the tensile strength of woven Kevlar/ epoxy to compare three different curing processes (pressure only, vacuum and pressure, and vacuum only). It was stated that a higher presence of pressure during the curing process results in a lower volume fraction. The tensile strength decreased as the volume fraction increased while the tensile modulus increased when the volume fraction increased. Thus, results showed that samples cured under vacuum only result in higher tensile strength. Samples cured under pressure only had a higher tensile modulus than when vacuum assisted or cured with vacuum only. However, vacuum and pressure cure results in fewer voids compared to the other two cycles.

Chapter 3

Methods

A thermogradient temperature is present in cryogenic propellant tanks during fueling. Usually the tank is at room temperature until subtle exposure to cryogenic temperatures from (LOX or CH_4). However, no commercially available environmental chamber to simulate a thermogradient temperature difference exists to this date. Current research done to investigate the mechanical properties of carbon fiber and Kevlar composites fully induce the samples in Liquid Nitrogen or dry ice. Others use environmental chambers to test samples at specific cryogenic temperatures while some just text their samples at room temperature. None consider the thermogradient temperature cryogenic tanks experience, making it challenging to rely on the mechanical properties obtained for real world applications (aerospace, infrastructure, etc).

Therefore, an environmental chamber was designed to expose samples to room temperature (25 ℃) on one face and cold temperature on the other (-60 ℃). If it can properly mimic the thermogradient temperature in the samples then colder temperatures can be explored.

3.1 Experimental Setup

The novel environmental chamber idea consists of a foam cooler with a lid, FORMULAR foam insulation and a heating source. A foam cooler was picked because it already provides some sort of insulation. Samples were secured at the top of the foam lid with low-temperature resistant double-sided tape. The environmental chamber was placed inside a fridge that can reach up to -60 ℃. This will help a sample experience a thermogradient temperature by being expose a sample to ambient temperature on one face and -60 ℃ on the other.

Without a heating source, it takes an average of 6.22 minutes for the inside temperature to reach negative temperatures as shown in Fig. 5,Fig. 6, and Fig. 7. Trial 3 took the longest of all three trials to reach a negative temperature due to some modifications done on the cooler to help prevent the heat escape. This included insulating the interior with FORMULAR foam insulation.

Results showed that a heating source was required to maintain room temperature inside the insulated box. With the addition of the heating source, the temperature of 23 ± 2 ℃

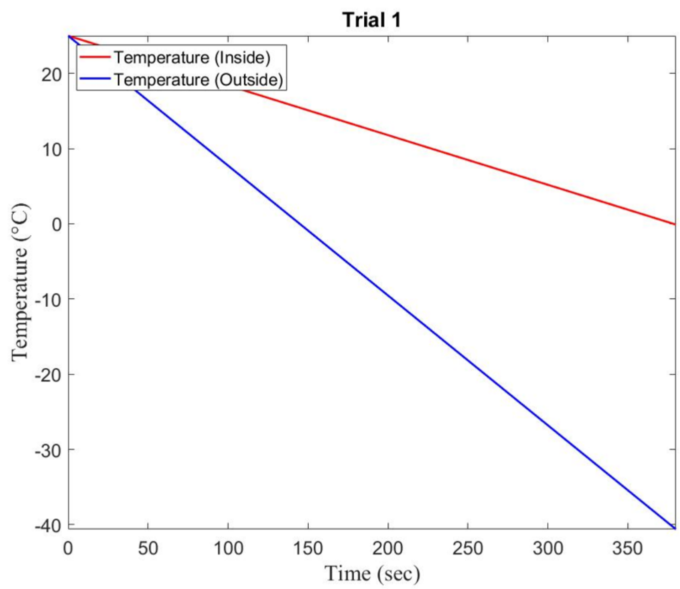

Figure 5: Trial 1 - Environmental Chamber Without a Heat Source

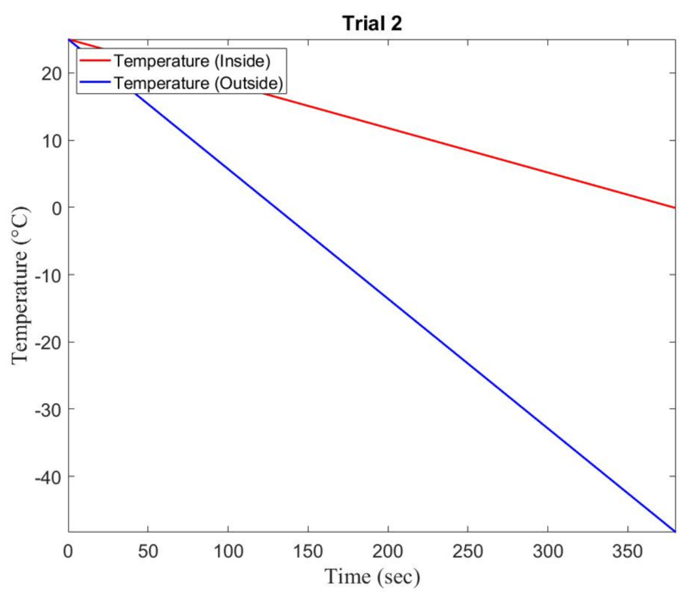

Figure 6: Trial 2 - Environmental Chamber Without a Heat Source

was able to be maintained for more than 20 minutes effortlessly.

The location of the samples within the coolers lid was also investigated. Two potential sample exposures configurations were considered. Configuration 1 has a face of the sample exposed to the cold temperature and a slight opening from the inside of the cooler exposed to room temperature. Configuration 2 has a face of the carbon fiber sample completely exposed to the ambient temperature inside the box with a small opening on the opposite side exposed to the cold temperature. Configuration trials were conducted for 20 minutes

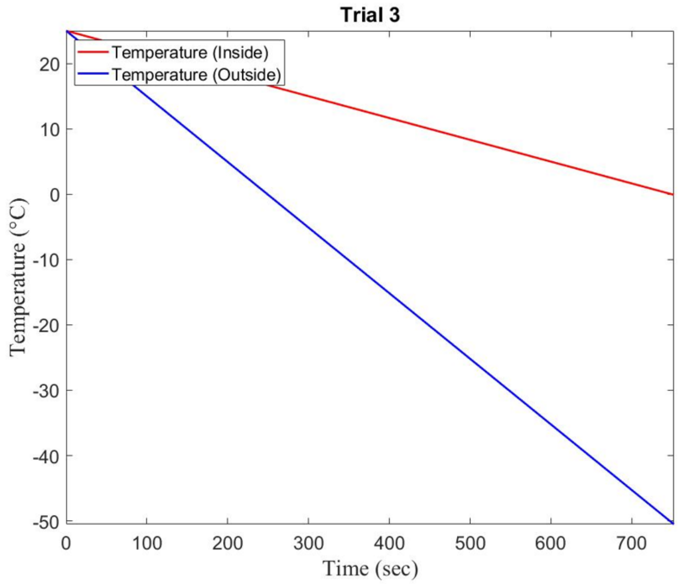

Figure 7: Trial 3 - Environmental Chamber With Insulation and Without a Heat Source

each for comparison. It is important to mention that all the trials conducted prior to actual conditioning were done with spare carbon fiber samples.

For configuration 1, the temperature of the sample facing the heating source was -7.8 ℃ and -43.6 ℃ on the face exposed to the -60 ℃. Results are expressed in Fig. 8.

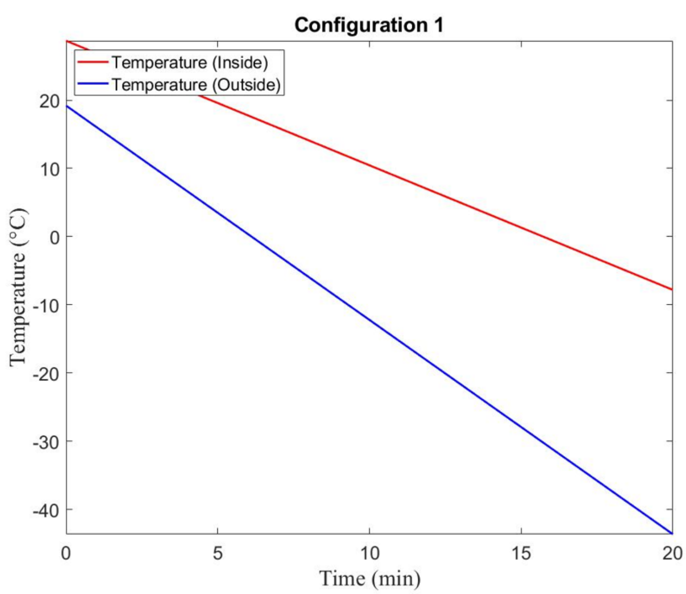

Figure 8: Configuration 1 Results After Exposure at -60 ℃

For configuration 2 the temperature of the sample facing the inside of the cooler did not drop to the negatives like configuration 1. However, since the sample is closer to the heating source in this configuration, it prevents the opposite face of the sample from reaching a lower temperature while in the freezer. Also, it was noticed that creating an opening in the foam lid for the samples often made the hole was bigger than required. Although it was covered with double sided tape to the best of our abilities, it is extra space for the heat to escape from the inside of the cooler. For this configuration (Fig. 9), the temperature of the sample facing the heating source was 13.8 ℃ and -18.5 ℃ on the face exposed to the -60 ℃.

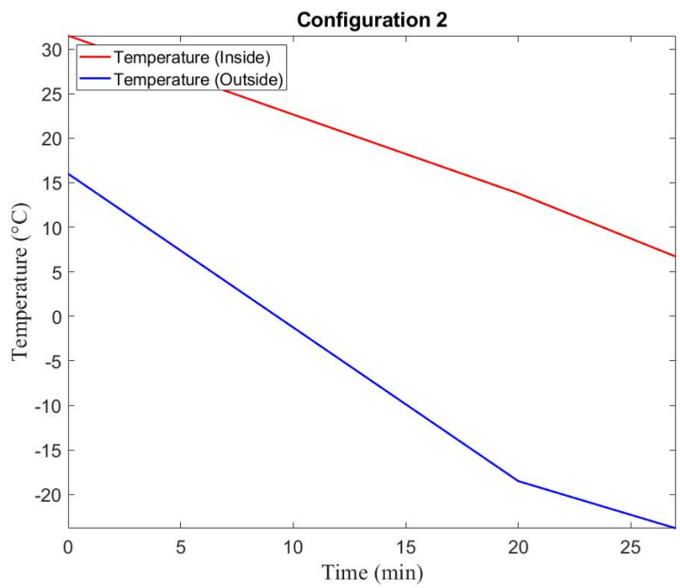

Figure 9: Configuration 2 Results After Exposure at -60 ℃

Based on the results obtained, it was decided to further elaborate and improve configuration 1 for it's the most relevant application to imitate the temperature difference cryogenic tanks experience. Ultimately, configuration 1 was picked because although the inside temperature reached negative temperatures, an even lower temperature was experienced on the outside surface. Ideally it is preferred to reach a lower temperature on the outside surface face exposed to the cold temperature. Especially when the lowest temperature that can be achieved during this scenario is -60 ℃.

To further maintain a room temperature inside the now insulated foam box (environmental chamber) a heating source was incorporated. The heating source was placed inside the cooler to help maintain a room temperature inside the cooler. It is important to mention that it is easier to control a hot temperature versus a cold temperature. The heat source being used provides a controller to adjust the temperature between -12 ℃ and -6 ℃ above ambient temperature (up to 42 ℃). Dimension and a visual representation of the environmental chamber is demonstrated in Fig. 10. Detailed anatomy of the environmental chamber is represented by Fig. 11. Fig. 12 demonstrates the temperature a sample is experiencing when foxed to an environmental chamber inside the fridge with the heating source on.

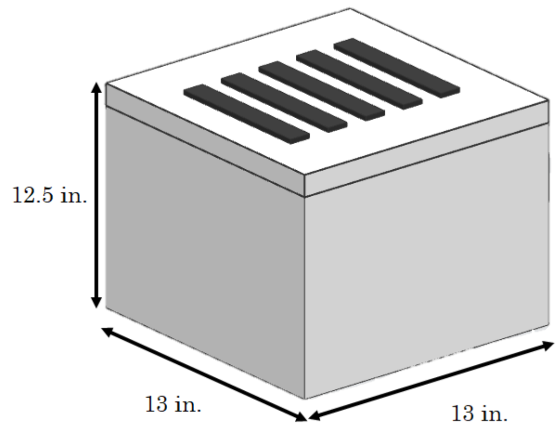

Figure 10: Environmental Chamber Dimensions

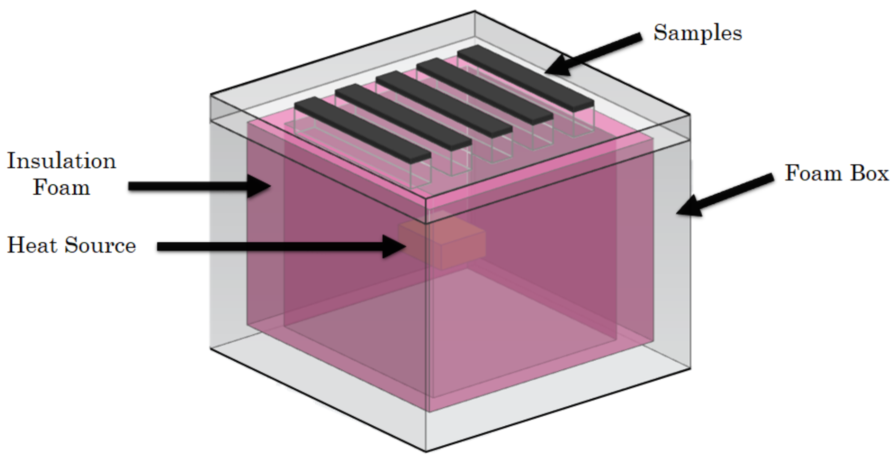

Figure 11: Environmental Chamber Anatomy

As mentioned earlier, samples were fixed to the environmental chamber with double sided tape. It could be possible that the amount of double-sided tape layers used affects the rate heat inside the heater escapes. To better understand the effect double-sided tape layers, have with temperature drop, several trials were conducted. Trials lasted an hour for comparison purposes.

Results showed that for multiple layers of tape there was approximately a temperature difference of 20 ℃. For trial 1, the temperature of the samples facing the heat source was -4.7 ℃ and the temperature of the face exposed to the cold temperature was -39.2 ℃(Fig. 13).

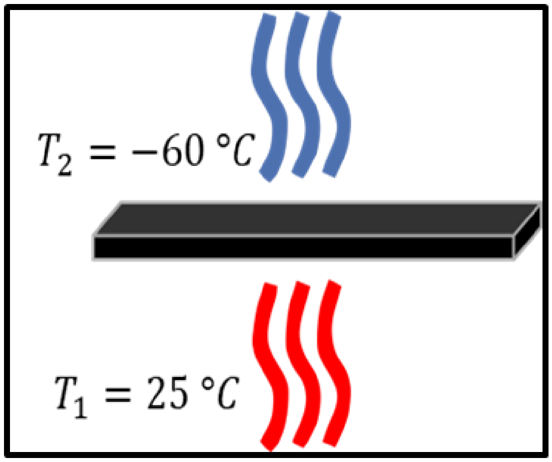

Figure 12: Thermo Gradient Temperature

Fig. 14 represents results from trail 2. The temperature of the samples facing the heat source was -7.6 ℃ and the temperature of the face exposed to the cold temperature was - 27.3 ℃.

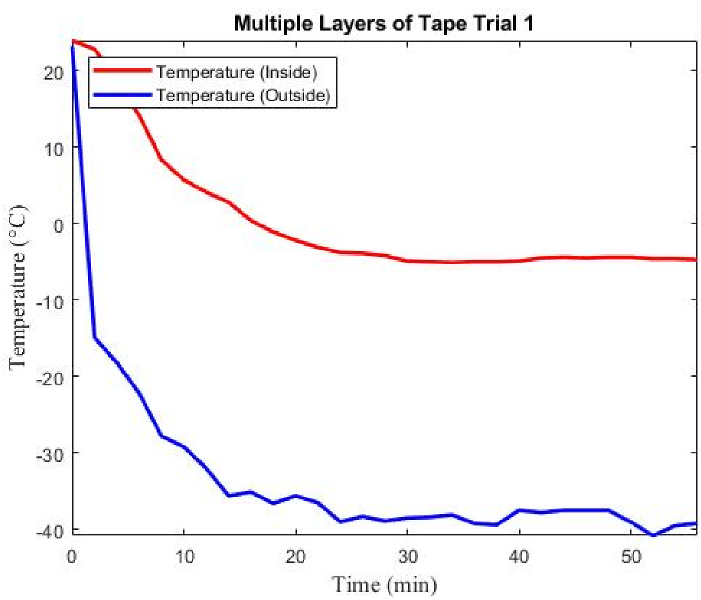

Figure 13: Results for Multiple Layers of Tape Trial 1

On the other hand, the temperature difference for a single layer of tape was between 5 to 10 ℃. The temperature of the samples facing the heat source was -19.1 ℃ and the temperature of the face exposed to the cold temperature was -30.5 ℃ for trial 1 (Fig. 15). For trial 2 (Fig. 16), the temperature of the samples facing the heat source was -20 ℃ and the temperature of the face exposed to the cold temperature was -25.8 ℃.

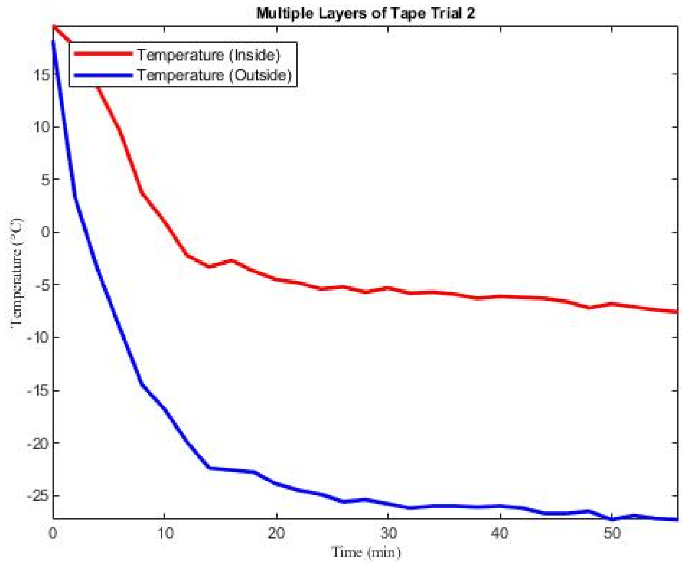

Figure 14: Results for Multiple Layers of Tape Trial 2

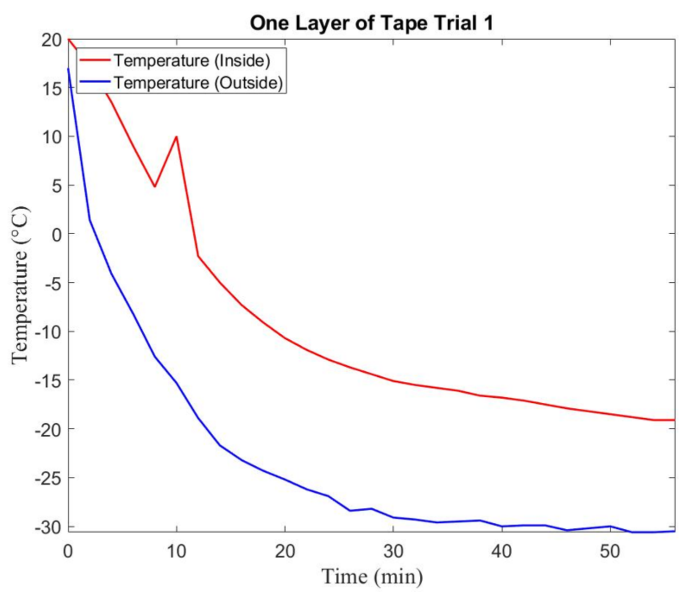

Figure 15: Results for a Sinlge Layer of Tape Trial 1

In conclusion, the amount of tape used does make an impact. Ultimately a higher temperature difference is preferred. Thus, it was decided to use more than one layer of tape when fixing the samples to the environmental chamber.

The time it takes for the temperature of the inside the environmental chamber with a heat source and the temperature on the outside surface of the samples to stabilize was also investigated. This will provide insight as to how long the samples need to be conditioned for.

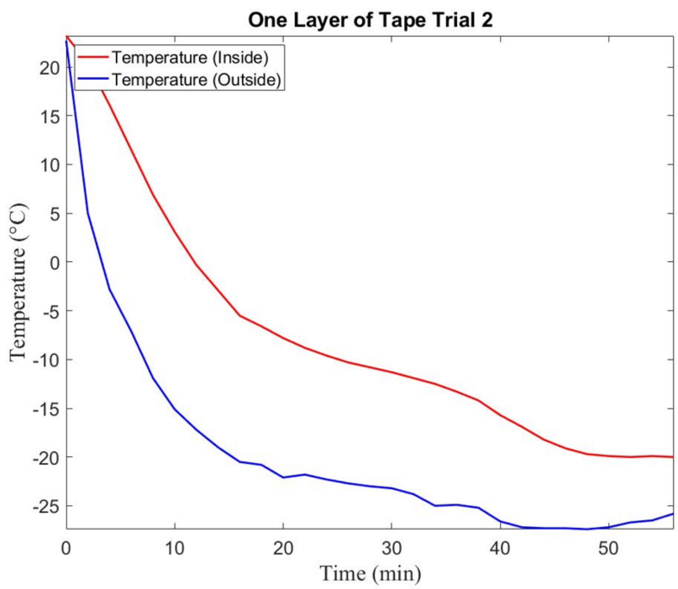

Figure 16: Results for a Single Layer of Tape Trial 2

The environmental chamber with a single layer of double-sided tape was placed in the fridge with the heat source on. The environmental chamber was not removed until the temperature being read by the thermocouples stopped fluctuating and stabilized. Results showed that temperature fluctuation stops after 40 minutes of exposure and it remains the same for 4 hours (Fig. 17).

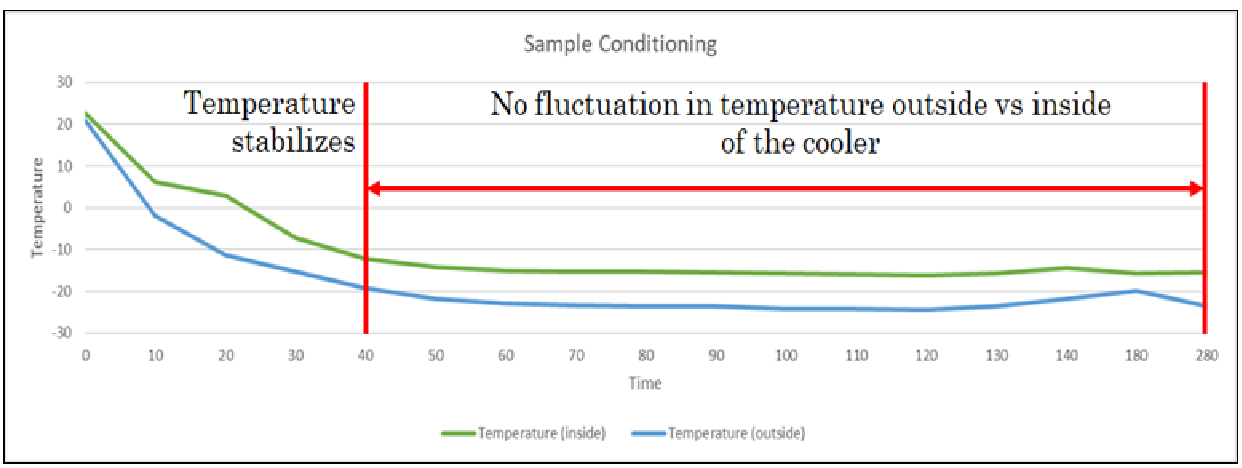

Figure 17: Long Time Exposure at -60 ℃

3.2 Manufacturing

According to literature review, woven fabric reduces crack propagation, gas permeability and an increase of stiffness at cryogenic temperatures. An epoxy resin was picked over other types of resins for its high fracture toughness, best average tensile strength, and maximum strain average. The chosen resin was Epon 828 and Epikure 3015 was picked as the respective hardener. 3K Plain weave woven carbon fiber was bought from Fiber Glast (https://www.fibreglast.com/) and the Epon 828 and Epikure 3015 were purchased from Hexion.

Although there is no ASTM standard for the manufacturing process of the woven composites, current published research was used to determine the number of layers of woven fabric and the adequate specimen dimensions. Ma et al.[26] specimens had a mean thickness of 1.46 mm while Sanchez-Saez et al.[13] samples were 1.6 mm thick. It was decided to manufacture specimens for a 90° fiber orientation according to the Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials ASTM D3039/D3039M - 17. From the spare samples used to test the environmental chamber it was known that a 16-layer woven carbon composite has an average thickness of 3.5 mm. This information was used to determine the number of layers required to manufacture a 2 mm thick specimen.

12 layers of plain weave carbon fiber and Kevlar was cut to dimensions of 304.8 mm (length) by 304.8 mm (width) along with four infusion flow media layers, eight release film layers, and four layers of breather. The CFRP composites were manufactured using the VARTM process. All layers were placed over an aluminum mold as shown in Fig. 18 and wrapped twice with Stretchlon 800 bagging film and secured with vacuum-sealant tape. The first vacuum bag had an inlet for the resin to be infused through and outlet connector. The second bag applied continuous pressure during the curing process (80 KPa). Epon 828 and Epikure 3015 were placed in a desiccator to remove all the bubbles. A mixture of Epon 828 and Epikure 3015 was then catalyzed with a weight ratio of 100:50 as instructed by the manufacturer. A pipe attached to the inlet was submerged in the mixture while the outlet was connected to a vacuum pump operating at approximately 80 KPa. After infusion was complete, the inlet was closed, and the laminate was left to cure for 24 hours under a constant pressure of 80 KPa. The procedure was repeated for both Kevlar and carbon fiber laminates.

Samples for tensile testing were then water-jet cut to dimension according to the ASTM standard. Sample dimensions are represented by Fig. 3.19(a) and Fig. 3.19(b).

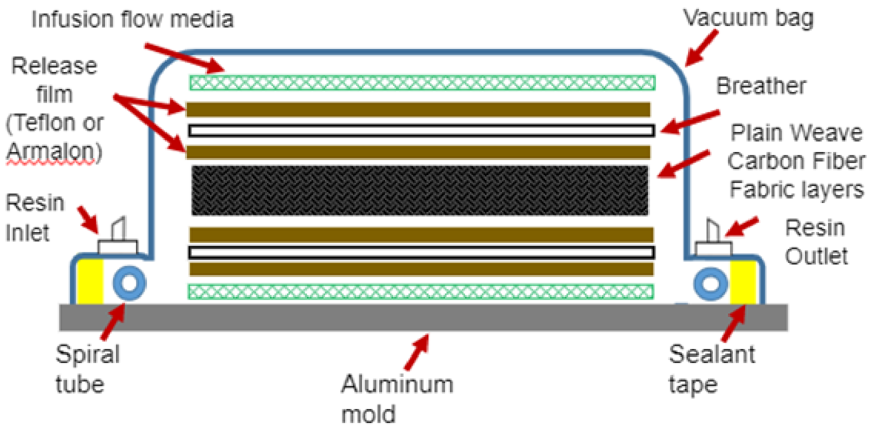

Figure 18: Vacuum Assisted Resin Transfer Molding (VARTM) Process

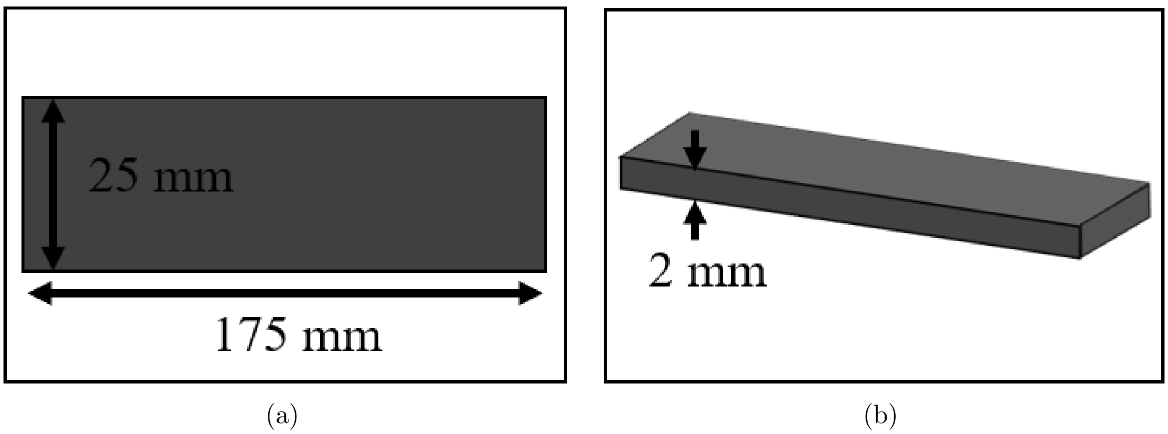

Figure 19: (a) Tension Sample Top View; (b) Tension Sample Thickness

In order to further investigate the material properties of Epon 828 and Epikure 3015, resin specimens were also manufactured. Molds for specimens were 3D printed with appropriate dimensions (Fig. 3.19(a)) according to the Standard Test Method for Tensile Properties of Plastics (ASTM D638 - 14). A weight ratio of 100:50 as instructed by the manufacturer of Epon 828 and Epikure 3015 was mixed. After mixing resin and hardener it was carefully poured in the molds and placed inside a compression press to cure. The compression press was set to 95 ℃ and molds were left to cure for two hours. After curing specimens were carefully removed from molds.

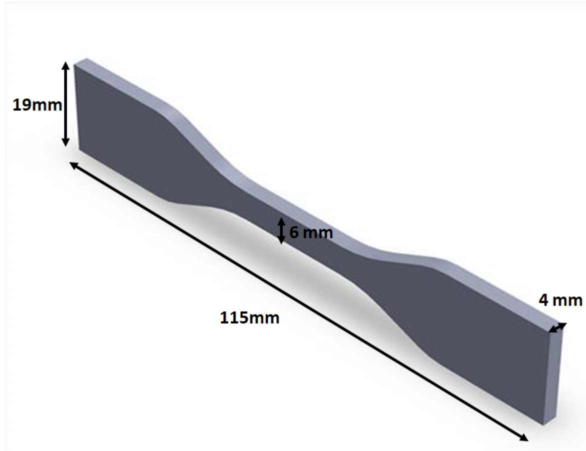

Figure 20: Resin Tension Sample Dimensions

3.3 Testing

To fulfill this thesis project objective of obtaining the mechanical properties of woven/epoxy (Kevlar and carbon fiber) composite materials the following approach(Fig. 21) will be taken. Composite samples will be tensile tested at 25 ℃, after exposure to -60 ℃ and with a thermal gradient. Resin samples will only be tested at 25 ℃ and after exposure to -60 ℃. The reason why resin samples will not be exposed to a thermal gradient temperature is because of its high thermal expansion coefficient. Thermal expansion coefficient in composites, for example, is low so when exposed to two different temperatures the difference in temperature can be maintained longer without contracting as much. However, resin contracts a lot more when exposed to cold temperatures which is why the matrix is always the first to fail in a composite. Even if attempted, a thermogradient wouldn't be possible in a resin sample. The difference in temperatures wouldn't be able to be maintained and the resin sample would reach a colder temperature faster.

The goal of the project is to prove the potential of textile (woven) composites in aerospace structures for cryogenic applications. Fig. 22 represents the planned approach to tensile test woven composites and resin samples at cryogenic temperatures. Woven composite samples (Kevlar and carbon fiber) will be tested without any exposure to cold temperatures, and after full exposure to -60 ℃ and -196 ℃. For thermogradient exposure, composite samples will be tested after two different temperature exposures of -60 ℃/25 ℃ and -196 ℃/25 ℃. Resin samples will be tensile tested at 25 ℃ without any exposure to cold temperatures and after full exposure to -60 ℃ and -196 ℃. Items in green boxes represent samples that have

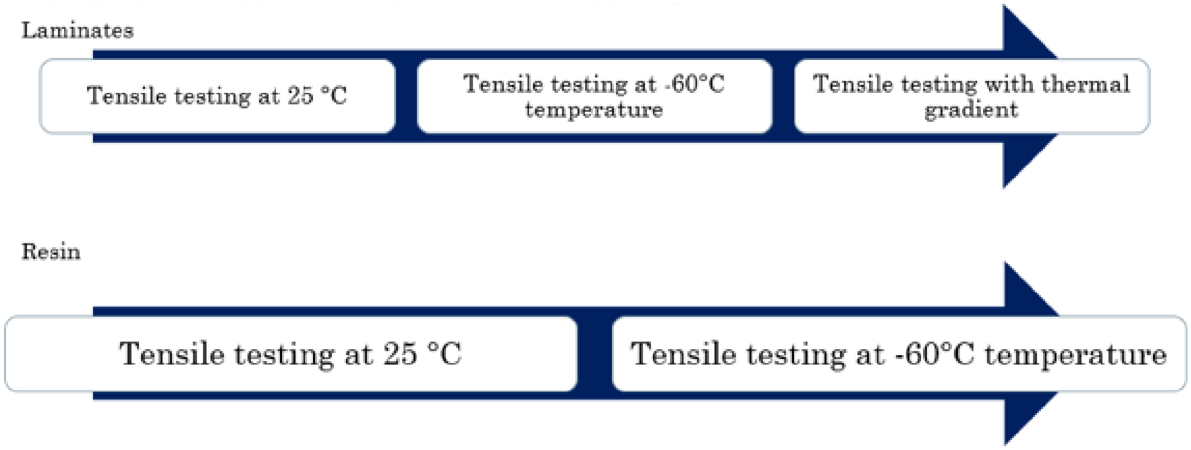

Figure 21: Tensile Testing Approach

already been tested while items in red boxes represent samples that are still in the process of being tested.

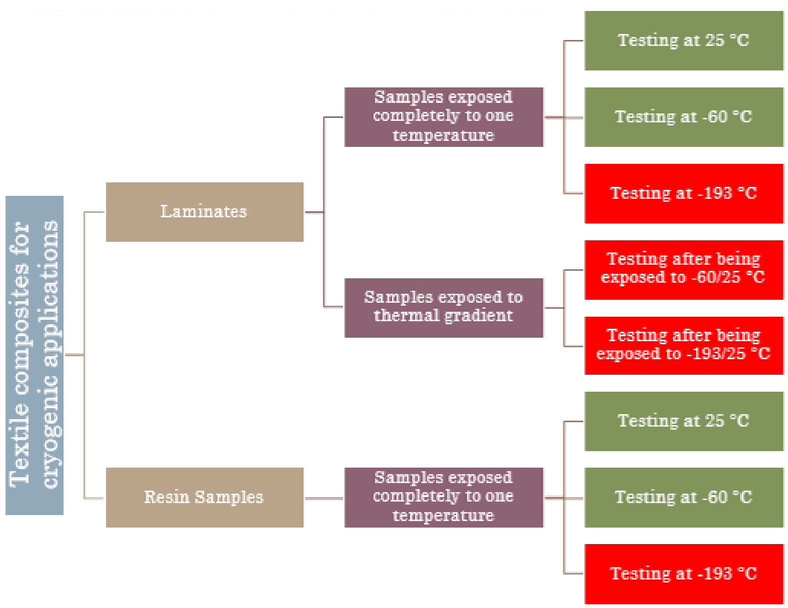

Figure 22: Future Tensile Testing Approach

Prior to conducting tensile testing samples where conditioned. Five samples of carbon fiber and five samples of Kevlar were fixed to the designed environmental chamber. The environmental chamber was placed inside the fridge (-60 ℃) for 5 hours and tested right after conditioning. Besides the conditioned samples, some composite samples were tested without any conditioning and others were tested after being fully exposed to -60 ℃ for mechanical behavior comparison purposes.

Five resin samples were placed inside the fridge at -60 ℃ for 48 hours while five resin samples were not exposed to any arctic temperatures.

Tensile testing was performed in an Instron Fatigue 8801 (Fig. 27) at room temperature according to the ASTM D30396 with a crosshead rate of 2 mm/min.

Figure 23: Instron Fatigue Machine 8801

Resin samples were tensile tested using an ADMET eXpert 1000 (Fig. 24) at room temperature according to the ASTM D638 - 14 (Standard Test Method for Tensile Properties of Plastics) with a crosshead rate of 5 mm/min.

Figure 24: Instron Fatigue Machine 8801

Chapter 4

Design of a Linerless Composite Tank for Cryogenic Applications

4.1 Introduction

Carbon composites are lightweight, have low thermal conductivity, have a high stiffness-to-weight ratio, and a high strength-to-weight ratio. Tensile strength of steel can range between 400 to 690 MPa, for example, while for composites it can vary between 1,200 to 2.410 MPa[27]. Since 1970 carbon fiber polymer composites have become of great interest including but not limited to aerospace, military, and aircraft[28]. Multiple projects have been funded to understand better their capabilities and ways of incorporating them into aerospace structures.

Kevlar has a high elastic modulus, high strength – to- weight ratio (five times better than steel), and widely used in composite applications. It is often use as bullet proof material on vests or laboratories walls; thus, it has high energy absorption capabilities and high toughness[24]. However, although it has high tensile strength it is not often used due to the poor adhesion of Kevlar with epoxy matrices that result in poor mechanical properties and delamination. The chemical inertness and smooth finish of the Kevlar prevent the fabric to properly adhere and although numerous post processing techniques (etching, grafting laser, plasma treatment and chemical coating) have attempted to improve interfacial properties, the issue with low- efficiency and the negative impact on mechanical properties still prevail.[23][25]

However, not much research has been done to better understand the mechanical properties of composite materials (carbon or Kevlar) in cryogenic environments for aerospace structural applications in liner-less pressure vessel tanks. Both Gates[10] and Whitley[9] studied the effects that preconditioning has in specimens (polymeric-matrix composite) and agreed that stiffness and strength is affected as temperature decreases when in tension. Mechanical properties were affected (higher stresses and lowest strength) in samples preconditioned for a prolonged period at cryogenic temperatures. Fujun Xu et al ([23]). Studied the tensile strength of Kevlar-129 fiber after cryogenically (77 K) treating the fiber/epoxy samples comparing temperature program-controlled method (TPCM) and quenching method (QM). He concluded that cryogenic treatment increases tensile strength of Kevlar fiber by 24.9% when conditioning with QM.

Aside from tensile strength, other factors need to be explored such as gas permeability, delamination and crack propagation for a liner-less common bulkhead pressure-fed carbon composite tank to be possible. Though through the few attempts to design a cryogenic composite tank (DC-XA, X-33, and CCTD) it has been concluded that in order to contain gas permeability and crack propagation a liner (polymer or aluminum) is required if a cryogenic composite tank wants to be used for aerospace structures.[6][7]. Unfortunately, a pressure-fed system tank for a launch vehicle that needs to go from ground to obit operate at high pressures (over 1,000 psi). Thus, the margin will be determined from the material system (fabric and matrix) chosen for the cryogenic tank. For UTEP's cryogenic tanks, the goal is to have a liner less tank for weight savings, and it is possible according to a patent open to the public by Composite Technology Inc (CTD)[3]. CTD offers commercially available liner-less carbon composite pressure-vessels. Although no details are offered regarding manufacturing process of these tanks, they do state that their tank are made from woven carbon fiber. In fact, one of their liner-less pressure vessels can withstand up to 5500 psi pressure loads made solely from braded plies.

Composite Cryogenic Technology Demonstration Project (CCTD) proved through testing weight reductions up to 30% and reduced costs by 25%[6]. This weight reduction allows for a pressure fed system to be possible. A high-pressure source is required, typically Helium, and it can be heavy depending on how much pressure is required to send oxidizer and fuel down to the engine. However, if weight is being reduced using composite tanks, the remaining mass budget can be used to accommodate the weight of a pressure fed system. Not to mention that common bulkhead tanks also contribute to weight reduction and launch vehicle size reduction. It has been over 50 years that common-bulkhead tanks have not been built since Saturn V S–II due to manufacturing issues. Air gaps and layers made it challenging, but with carbon composites this issue can be eliminated[29]. Whether it is through pre-impregnated (pre-preg) laminas or filament winding, if manufactured properly, air gaps will be accounted for.

It is with the intention of this research to investigate the mechanical response of carbon fiber/epoxy composites and compare it to those of Kevlar/epoxy to understand its mechanical behavior when exposing samples at artic temperatures. There is no doubt that a thermo-gradient temperature exists from when the cryogenic propellant liquids are drained into the cryogenic tanks. Current research conducts tensile testing in an environmental chamber or after conditioning sample through full exposure to liquid nitrogen. Neither of these account for the thermal gradient, they only allow for the investigation of mechanical properties of carbon fiber composites after exposure to cryogenic temperatures. For this reason, a novel conditioning method has been developed to expose one face of the sample to -60 ℃ and the opposite face at 25 ℃ Tensions tests will be performed to evaluate the stiffness and strength degradation of these composites when exposed to two different temperatures (Cryogenic and room temperature) on their surfaces. For comparison purposes, tensile testing will also be conducted on samples conditioned at -60 ℃ and on samples without any conditioning (25 ℃) or exposure to artic temperatures.

4.2 Methods

A plain weave woven carbon fiber polymer matrix composites were manufactured using the vacuum assisted resin transfer molding VARTM process. The Epoxy used was EPON 828 and the respective hardener was EPIKURE 3015. Woven fabric was chosen versus cross ply because in a study done by Choi et al. ([14]) they discovered that although some microcracks developed after exposing the textile lamina at cryogenic temperatures these never connected and concluded that there is less gas permeability on woven versus cross-ply. McBride et al. ([16]) studied the tensile properties of three different epoxies for structural applications, among them EPON 828. Results showed that this resin had the best average tensile properties of 49.6 MPa.

4.2.1 Material Selection

3K Plain weave woven carbon fiber was bought from Fiber Glast (https://www.fibreglast.com/) and the Epon 828 and Epikure 3015 were purchased from Hexion. Their respective material properties can be found in Table 4.1.

From CCTD project it was found that vacuum-bag only cured composite laminas that resulted in less porosity, better mechanical properties and quality than expensive autoclave curing. It was also found that just with 12 plies permeability performance required can be achieved and provide protection against microcrack[6].

Table 4.1: Mechanical Properties of Materials

Mechanical Properties	Woven Carbon Fiber	Woven Kevlar Fiber
Tensile Modulus (MPa)	2275-2406	112
Tensile Strength (MPa)	4200-4400	3000-3620
Density (kg/m^3)	1750-2000	1440
Nominal Thickness (mm)	0.3048	0.279

4.3 Manufacturing methods

The CFRP composites were manufactured using the VARTM process, which is shown in Figure 1. Two infusion flow media layers, four release film layers, two layers of breather, and 12 layers of woven carbon fiber were cut to dimensions of 304.8 mm (length) by 304.8 mm (width). Dimensions and number of carbon fiber layers were picked according to the Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials ASTM D3039/D3039M - 17. Then all the layers were placed over an aluminum mold and wrapped twice with Stretchlon 800 bagging film and secured with vacuum-sealant tape. The first vacuum bag had an inlet and outlet connector for the resin to be infused through. The second bag contained a connector that would apply continuous pressure during curing process (80 KPa). The EPON 828 was catalyzed with EPIKURE 3015 with a ratio of 100:50, respectively as recommended by the manufacturer. Air bubbles were removed from the resin and hardener individually using a desiccator. The resin and hardener were then mixed, and the inlet was submerged into the mixture. The outlet was connected to a vacuum pump with an approximate pressure of 80 KPa. When infusion was completed, it was left to cure for 24 hours under a constant pressure of 80 KPa. From each laminate, specimens were water jet cut for tension. Fig. 25 and Fig. 26 show the sample dimensions.

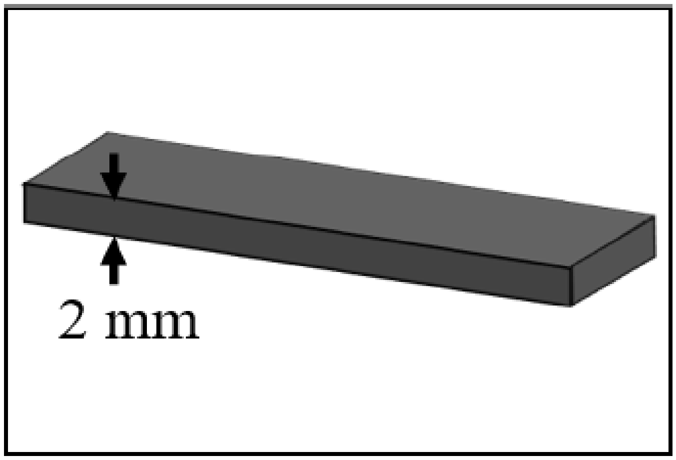

Figure 25: Sample Thickness for Tension Required by ASTM D3039/D3039M-17

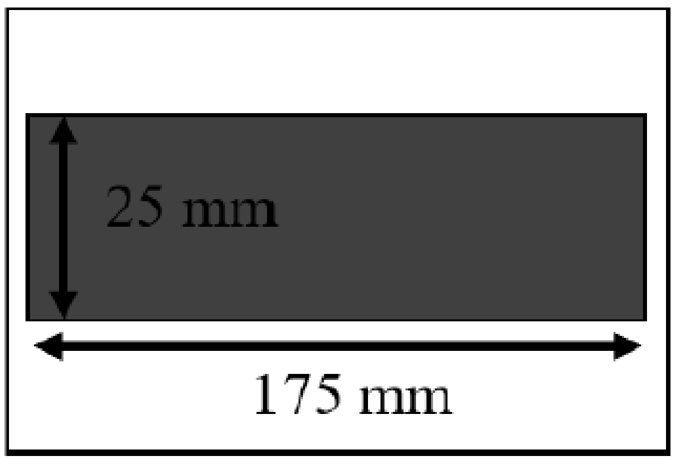

Figure 26: Sample Length and Width for Tension Required by ASTM D3039/D3039M-17

4.4 Tensile Tests

The specimens will be exposed in one side to -60 ℃ and 25 ℃ in the other side. The samples will be exposed to this thermal gradients for five hours, then they will be tested under tensile loading. The tests will be performed in an Instron Fatigue 8801 (Fig. 27) according to the ASTM D30396 with a crosshead rate of 2 mm/min.

Figure 27: Instron Fatigue Machine 8801

4.5 Conclusions

Aerospace structures can benefit from carbon composites mechanical properties. However, it is crucial to first understand carbon fiber/epoxy laminates behavior when exposed to cold temperatures and exposed to tensile stress. Components have been manufactured and sent to water jet cut. Testing is expected to take pace in the upcoming weeks. Results will be used to create a finite element analysis damage model in the future. The mechanical properties of the matrix picked will help determine if it's an adequate material system for a liner-less pressure fed common bulkhead cryogenic tank.

Chapter 5

Matrix System

Tensile test data was collected from both ADMET eXpert 1000 and Instron Fatigue 8801and post processed. The best two trials were chosen for demonstration from the five tensile tests conducted on composite samples and resin samples. Fig. 28 represents the results obtained from the composite samples without any exposure to arctic temperatures and tested at room temperature. For trial 1, the Young's modulus was 33.684 GPa while the ultimate tensile strength (UTS) and failure strain was 550.17 MPa and 1.48 respectively. For trial 2, the UTS and failure strain was 622.25 MPa and 1.47% respectively making the Young's Modulus 39.14 GPa. The average Young's modulus of all textile composites was 40.31 GPa. The average UTS and failure strain was 550.6 MPa and 1.64% respectively.

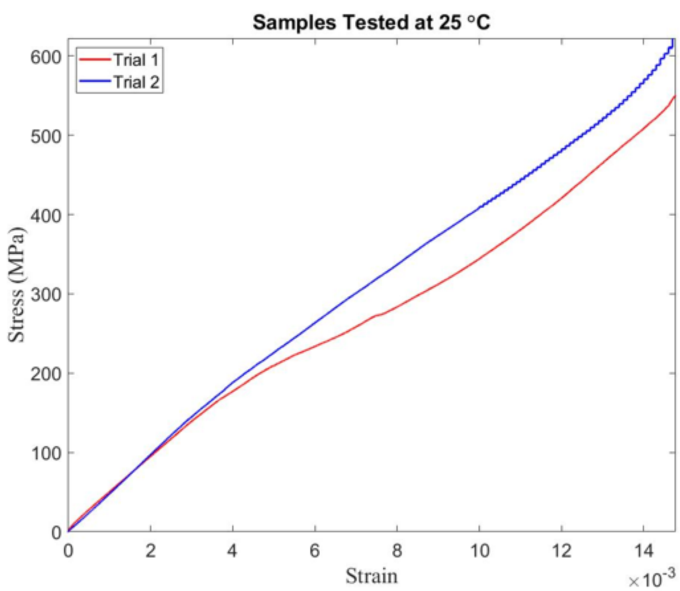

Figure 28: Stress-Strain Curve of Composite Samples Tested at 25 ℃

Results of composite samples tested after exposure to -60 ℃ are shown in Fig. 29. The Young's modulus and tensile strength for trial 1 was 35.6 GPa and 576 MPa respectively. The Young's modulus and tensile strength for trial 2 was 40.1 GPa and 638.9 MPa respectively. Both trials had a strain at failure of 1.5%. The average Young's modulus of all textile composites was 40.8 GPa. The average UTS and failure strain was 612.7 MPa and 1.49% respectively.

Comparison between a sample tested at 25 ℃ versus a sample tested after exposure to

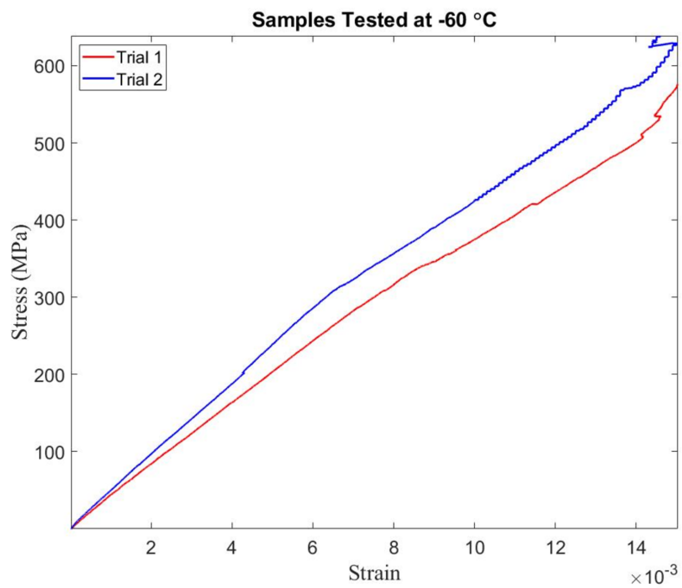

Figure 29: Stress-Strain Curve of Composite Samples Tested at -60 ℃

-60 ℃ is shown in Fig. 30. Textile carbon samples failed at a lower strain but had a higher average Young's modulus when exposed to -60 ℃. A higher ultimate tensile strength was seen in samples tested at -60 ℃ than those without any exposure to cold temperatures.

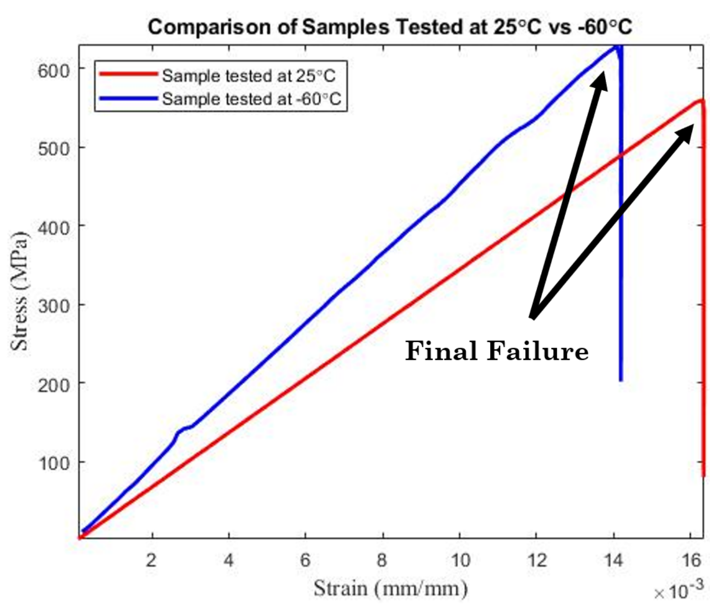

Figure 30: Comparison between Stress-Strain Curves of Samples Tested at 25 ℃ and -60 ℃

Textile carbon composites under tension only experience fiber breakage and delamination but never yielding deformation. Fig. 31 demonstrates the difference in damage between a carbon sample tested at 25 ℃ and a carbon sample tested after exposure to -60 ℃ (arctic temperature). After exposure to -60 ℃, the sample failed due to fiber breakage. The sample without exposure to a cold temperature experienced both fiber breakage and delamination at failure. Delamination occurs when the epoxy contracts while being exposed to cold temperatures.

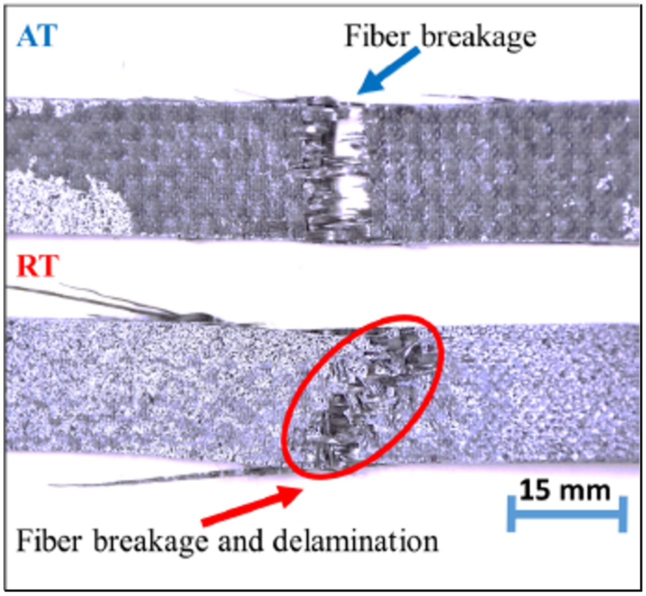

Figure 31: Damage of Samples Tested at 25 ℃ and -60 ℃

Resin samples tested at 25 ℃ had an average UTS of 46.4 MPa and an average failure strain of 1.61%. Stress- strain curve of a resin sample is shown in Fig. 32 with an average Young's modulus of 2.8 GPa. The average UTS and average failure strain of the resin sample exposed to -60 ℃ was 10.1 MPa and 0.38% respectively (Fig. 33). All resin samples failed due to resin breakage as shown in Fig. 34. UTS and strain failure were both smaller for resin samples at -60 ℃(fig). Resin samples with exposure to -60 ℃ failed before those without conditioning because resin becomes brittle at colder temperatures.

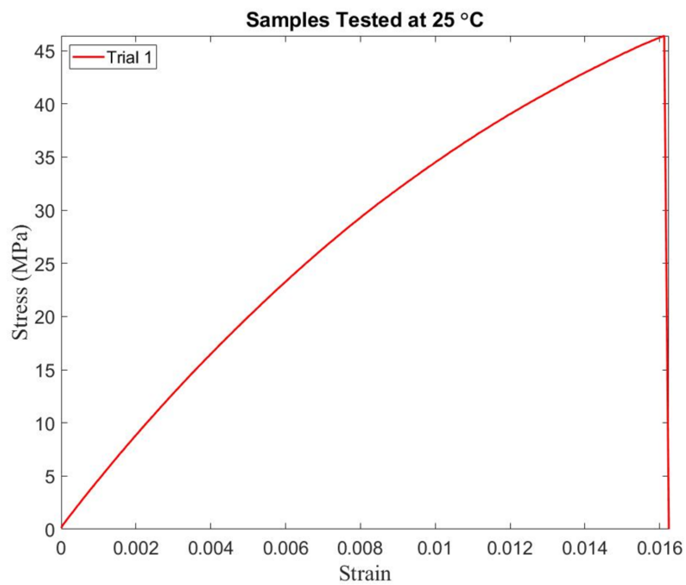

Figure 32: Stress-Strain Curve of Resin Samples Tested at 25 ℃

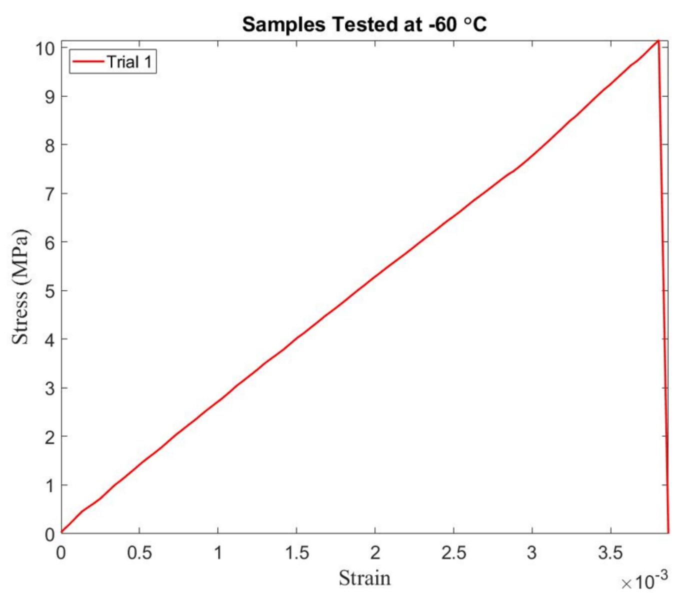

Figure 33: Stress-Strain Curve of Resin Samples Tested at -60 ℃

The specific strength and specific modulus were then compared for different materials such as 2000 series Aluminum, woven AS4 and woven carbon fiber (Fig. 35). The mechanical properties obtained from the tensile testing were used for this plot. As the specific strength and specific modulus approaches zero the material experiences poor strength-to-weight ratio. The material has a good strength-to-weight ratio and good modulus-to-weight ratio the further the ratio is from zero. Although Aluminum and carbon fiber have a similar specific

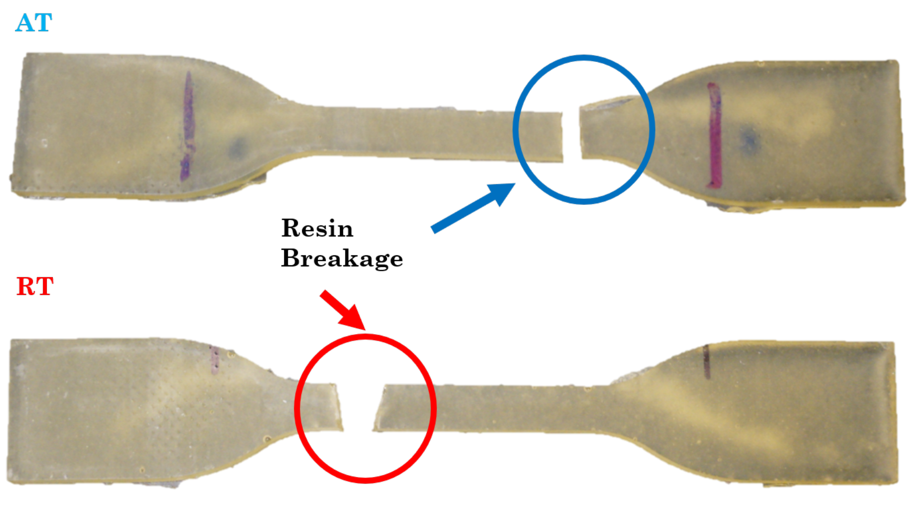

Figure 34: Damage of Resin Samples Tested at 25 ℃ and -60 ℃

modulus the specific strength of carbon fiber tested at 25 ℃ and -60 ℃ is higher and has a better strength-to-weight ratio. Woven AS4, which is a very expensive fiber, has an even higher strength-to-weight ratio and modulus-to-weight ratio than Aluminum.

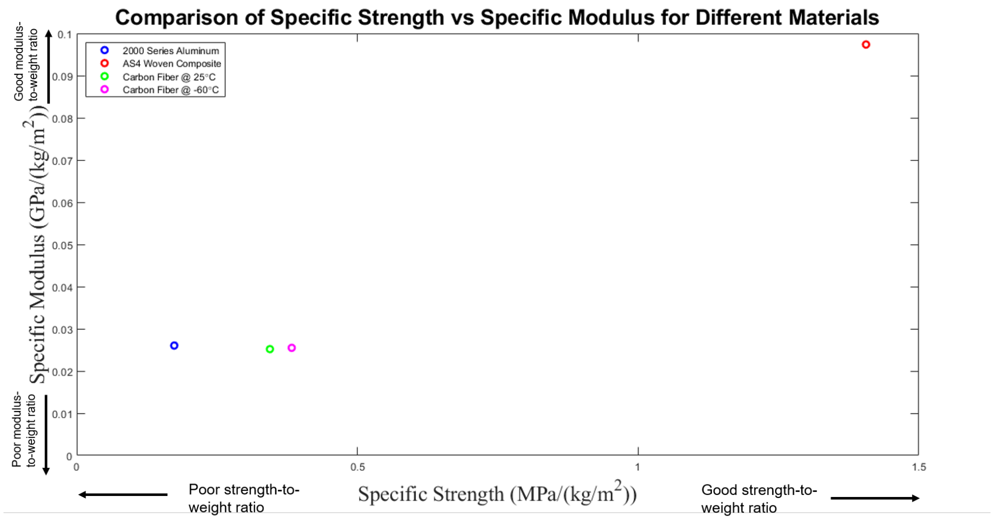

Figure 35: Specific Strength vs Specific Modulus

Chapter 6

Type 5 All Carbon Fiber Pressure Vessels Vs Aluminum Pressure Vessels

6.1 Unidirectional AS4 vs Woven Carbon Fiber

AS4 is a unidirectional fiber that is very expensive, and its mechanical properties are often misinterpreted and overvalued. A unidirectional composite strength is defined by two different values: axial and transverse tensile strength. Unidirectional AS4 can be viewed as a stronger and stiffer material because of its high axial tensile strength which follows the fiber direction(Table 6.2). However, in the transverse direction the tensile strength decreases significantly making AS4 stiffer only in the fiber direction. To account for the loss in the transverse direction more layers of unidirectional AS4 will be required resulting in a weight increase. On the other hand, woven carbon fiber has one tensile strength value and although it is not as high as the axial tensile strength of unidirectional AS4 it is constant through the axial and transverse direction. In addition, woven composites result in less crack propagation, less gas permeability and will require a smaller number of layers. When comparing mechanical properties between AS4 and the woven carbon fiber used for this experiment there is not much difference in the density of the composite. The difference in fiber volume fraction is due to the nature of the fiber and the manufacturing processes. Woven AS4 is available but very expensive which is why it was not purchased for this project but is a potential candidate for a cryogenic type 5 composite overwrapped pressure vessel.

Table 6.2: Mechanical Properties of Woven AS4 and Woven Carbon Fiber

Mechanical Property	Unidirectional (AS4)	Woven (Plain Weave)
Density (g/cm^3)	1.52	1.6
Axial Tensile Strength (MPa)	2137	612.7
Transverse Tensile Strength (MPa)	53.4	
Fiber Volume Fraction	0.62	0.45 - 0.5

6.2 Thickness of COPV vs Aluminum Pressure Vessels

According to the ASME Boiler & Pressure Vessel (BPVC) - Section VIII the safety factor for composite pressure Vessels must be between 3.5 and 6 and for metal pressure vessels must be 2.5. For the following calculations the aluminum UTS of 469 MPa, woven AS4 UTS of 2137 MPa, and woven carbon fiber UTS of 612.7 MPa was used. Woven carbon fiber UTS was obtained from tensile testing from this project. (6.1) was used to calculate the allowable stress of aluminum with a safety factor of 2.5 and the allowable stress of woven AS4 and carbon fiber at safety factors of 3 and 6. The allowable stresses calculated are shown in Table 6.3.

$$\sigma_{allowable} = \frac{\sigma_{UTS}}{S.F} \tag{6.1}$$

Table 6.3: Allowable Stress of Aluminum, Woven AS4 and Woven Carbon Fiber

Aluminum	AS4	Woven
$\sigma_{allowable}$ = 187.6 MPa	S.F of 3.5	S.F of 3.5
	$\sigma_{allowable}$ = 610.6 MPa	$\sigma_{allowable}$ = 175.1 MPa
	S.F. of 6	S.F. of 6
	$\sigma_{allowable}$ = 356.2 MPa	$\sigma_{allowable}$ = 102.1 MPa

From the tank calculations and requirements specified in Appendix A, the operating pressure for helium tank after considering the margin of safety of 1.63 is 9,780 psi. The thickness of the helium tank was calculated using (6.2) for a spherical thick-wall pressure vessel using the radius of 0.625 m when using the allowable stresses of Aluminum and woven carbon fiber. Where P is load, b is outer radius and a is the inner radius. Excel what-if analysis was used in to back calculate the thickness. (6.3) was used to calculate the thickness of a spherical thin-wall pressure vessel for woven AS4. For both the oxidizer and fuel tank the thickness was calculated using (6.4) for cylindrical thin-wall pressure vessels and (6.5) for the bulkhead of the tanks. These two equations were used for all three materials and their respective allowable stresses. Table 6.4 shows the calculated thickness for the helium, oxidizer and fuel tank for each material at different safety factors. The thicknesses in orange represent the cylinders and the bulkheads and spheres are in white boxes. There was a 76% decrease in thickness for woven AS4 when compared to the woven carbon fiber thicknesses. Tank thickness for the oxidizer and fuel tank were similar.

$$\sigma_{allowable} = \frac{P(b^3 + 2a^3)}{2(b^3 - a^3)} \tag{6.2}$$

$$\sigma_{allowable} = \frac{P * d}{2 * t} \tag{6.3}$$

$$\sigma_{allowable} = \frac{P * d}{t} \tag{6.4}$$

$$\sigma_{allowable} = \frac{P * d}{4 * t} \tag{6.5}$$

Table 6.4: Tank Thicknesses for Different Materials

<table>
<tr><th>Aluminum</th><th>AS4</th><th>Woven</th></tr>
<tr><td colspan="3">Helium (mm)</td></tr>
<tr><td>2.5 S.F</td><td colspan="2">3.5 S.F</td></tr>
<tr><td rowspan="3">80.48</td><td>34.5</td><td>86.76</td></tr>
<tr><td colspan="2">6 S.F</td></tr>
<tr><td>59.2</td><td>160.71</td></tr>
<tr><td colspan="3">Oxidizer (mm)</td></tr>
<tr><td>2.5 S.F</td><td colspan="2">3.5 S.F</td></tr>
<tr><td rowspan="2">8.83</td><td>2.43</td><td>9.57</td></tr>
<tr><td>4.86</td><td>19.14</td></tr>
<tr><td rowspan="3">17.67</td><td colspan="2">6 S.F</td></tr>
<tr><td>4.32</td><td>18.3</td></tr>
<tr><td>8.63</td><td>36.605</td></tr>
<tr><td colspan="3">Fuel (mm)</td></tr>
<tr><td>2.5 S.F</td><td colspan="2">3.5 S.F</td></tr>
<tr><td rowspan="2">8.94</td><td>2.44</td><td>9.69</td></tr>
<tr><td>4.89</td><td>19.626</td></tr>
<tr><td rowspan="3">18.1</td><td colspan="2">6 S.F</td></tr>
<tr><td>4.34</td><td>18.71</td></tr>
<tr><td>8.74</td><td>38.22</td></tr>
</table>

Using the thicknesses that were calculated, the volume of the helium and oxidizer tank were then calculated. The fuel tank was not included in the table since the thickness and volume values were similar. Using the volume and the respective densities of each material the mass was calculated. Table 6.5 shows the mass of both helium and oxidizer tanks in kilograms for different materials at different safety factors. Even at a safety factor of 6, woven AS4 helium, oxidizer and fuel tanks are lighter than aluminum. Aluminum might have a low safety factor requirement, but it is also denser meaning it will be heavier. Woven carbon fiber tanks are lighter than aluminum when using a safety factor of 3.5. However, at a safety factor of 6 they become heavier than aluminum tanks. A factor of safety of 6 is typically used for unidirectional composites to ensure reliability. In our case, considering a factor of safety of 6 won't be necessary.

Table 6.5: Tank Masses for Different Materials

<table>
<tr><th>Aluminum</th><th>AS4</th><th>Woven</th></tr>
<tr><td colspan="3">Helium (kg)</td></tr>
<tr><td>2.5 S.F</td><td colspan="2">3.5 S.F</td></tr>
<tr><td rowspan="3">1,209.9</td><td>272</td><td>780.4</td></tr>
<tr><td colspan="2">6 S.F</td></tr>
<tr><td>484.5</td><td>1,613.4</td></tr>
<tr><td colspan="3">Oxidizer (kg)</td></tr>
<tr><td>2.5 S.F</td><td colspan="2">3.5 S.F</td></tr>
<tr><td rowspan="3">713.9</td><td>96.8</td><td>464.1</td></tr>
<tr><td colspan="2">6 S.F</td></tr>
<tr><td>179.7</td><td>1,012.8</td></tr>
</table>

Chapter 7

Concluding Remarks

7.1 Significance of the Result

The intent of this project was to demonstrate that aerospace structures, such as cryogenic propellant tanks, can benefit using woven carbon composites with an epoxy matrix. Furthermore, prove how a pressure-fed liner-less common bulkhead carbon composite propellant tank can be manufactured. A competitive resin and textile fabric were chosen to manufacture laminas for tensile testing from an extensive literature review study. Results showed that carbon fiber samples tested at -60C had a 1.2% increase in Young's modulus than those without any conditioning. UTS and failure strain also increased by 22.5 % and 25.2% respectively. However, the Young's modulus of resin samples tested at -60 C decreased by 21.4% than those without any exposure to arctic temperatures. UTS and failure strain also decreased by 78.2% and 76.4% respectively. Thus, resin mechanical properties are affected and decrease as temperature decreases. Textile composites mechanical properties increased as temperature decreased but failed faster. The uniqueness and complexity of the core stage tank might come across as hard to manufacture specially if made from woven carbon fiber. However, companies such as CTD sells liner-less woven carbon fiber pressure vessels which are braided over a removable or dissolvable mandrel. Due to the lack of access to a machine used by companies such as CTD, small prototypes of the core stage tank components were made individually using braided carbon fiber biaxial sleeves and yarn instead. This showed how the manufacturing of tank components can be manufactured individually then assembled later. However, a larger scale would require more time and complex machines but it is possible.

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Appendix A

Core Stage Tank Dimensions and Analysis

7.1 Tank Dimensions

Current core stage requires 10120 lbs of propellant and has a mass budget of 2073 lbs for dry mass. Both the oxidizer and the fuel tanks must withstand pressures of 400 psi each. The Helium tank on the other hand, needs to be pressurized to 6000 psi. According to the literature review a margin of safety of 1.63 and a safety factor of 1.5 is acceptable. The mission required a 2.7 oxygen to fuel ratio. Using this ratio and the propellant mass, the required mass of oxidizer and fuel was calculated. These masses were then divided by its respective densities to calculate the required volume for each (oxidizer and fuel tank). Ullage, boiling, and trapped volume were also considered for both the oxidizer and fuel tank. The mass of Helium required was calculated by multiplying the required pressure by the total volume of oxidizer and fuel divided by the product of Helium's gas constant and its temperature. The volume required for Helium was calculated as well as the extra amount of Helium required to keep all three tanks (fuel, oxidizer, and Helium) pressurized to prevent them from collapsing as they emptied out.

No component in the core stage tank is spherical. The core stage tank is composed of a Helium, oxidizer, and fuel tank. Each tank component will be an assembly of a cylinder with half spheres on both or one end of the cylinder. To reduce the stress in the Helium tank, the cylinder will be as short as possible. When manufacturing the core stage tank, each manufactured component (Helium, oxidizer, fuel) will slide inside each other in that order and will then be secured with more layers of carbon fiber/ epoxy.

(A.1) was used to calculate the length of each cylindrical part in each component. (A.2) was used to calculate the thickness of a tank. (A.3) was used to calculate the length each component needs to overlap when being assembled and for precaution purposes the overlap length was tripled. Process was repeated for each core stage component to calculate thickness and length. A fixed inner diameter for the Helium tank of 45 inches was chosen. Since each component will slide into each other the thickness of the Helium tank will dictate the inner diameter of the oxidizer tank. The thickness of the oxidizer tank will dictate the inner diameter of the fuel tank and so on and so forth. All the thickness of the tanks and bulkheads are subject to change, but this will depend on results obtained from finite element analysis.

$$L = \frac{V * t}{\pi * r^2} \tag{A.1}$$

$$t = \frac{\eta * P * r}{2 * \sigma_{allowable}} \tag{A.2}$$

$$L_{overlap} = \frac{\eta * \pi * r^2 * P}{2 * \pi * r * \sigma_{allowable}} \tag{A.3}$$

Where L is length, V is volume, t is thickness, r is radius, P is pressure load, η is margin of safety, and $\sigma_{allowable}$ is carbon fiber allowable stress.

7.2 Finite Element Analysis in Hyperworks

An obstacle encountered while conducting finite element analysis was that the tanks were heavier than anticipated. Mathcad calculations provided and estimate as to how much the core stage tank will weight but it was not precise since the finite element analysis would consider the model to provide a more realistic weight for the core stage tank. It took several iterations to cad a tank that meet the requirements. Structural analysis was conducted using HyperMesh Optistruct. Since the tank is an assembly compose of the helium, oxidizer and fuel tank it was easier to mesh. Whenever the tank was CAD as one piece it was very challenging to try and mesh individual components due to all the lines of reference. For this reason, the tank was CAD as individual components and then assembled. Not only would it help to visualize a realistic manufacturing assembly, but it would also simplify things when it comes to doing analysis. The tank was analyzed without the fittings, only the main components where considered. The main reason why each component had to be mesh individually was so that each could be given a property where the thickness could be changed accordingly. In this case, the thickness had to be altered such as that the tank could withstand 1800-pound force at 6gs while maintaining a factor of safety of 1.5 and margin of safety of 1.63. The image below shows the tank meshed where each component is represented by a different color.

Notice how the helium tank is broken down into three different components. The color

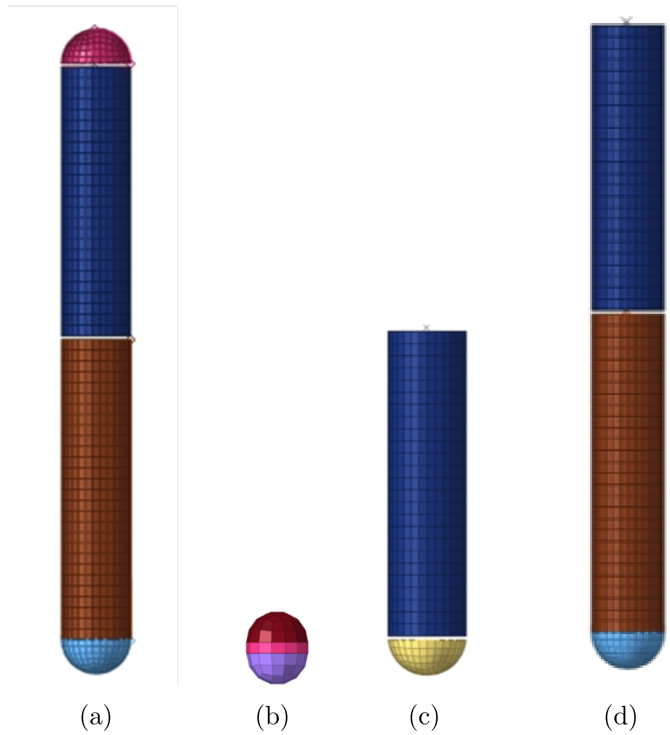
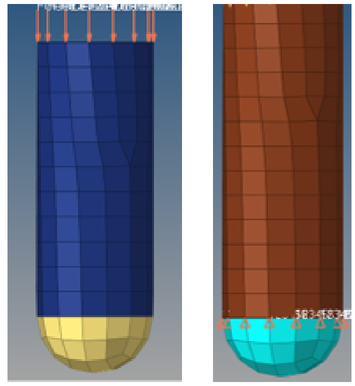


Figure 36: (a) Meshed Tank; (b) Helium Tank; (c) Oxidizer Tank; (d) Oxidizer and Fuel Tank

maroon and purple represent the semi-spheres while pink represent the cylinder, like the model that shown previously. The load will rest at the top border of the blue cylinder while being fixed at the bottom of the brown cylinder on the fuel tank. Reasoning behind this is that the inner stage will be resting on top of the helium tank while the bottom part of the core tank will be resting in the floor. Something important to note is that the force applied must be equally distributed among each of the nodes where the force is applied. In other words, if the load is 1800 by 6 gs in 20 nodes the force specified needs to be 1800 times 6 divided by 20. In this case, the load on each node was 720 pounds. Aside from the load applied to the tanks they were also applied a pressure to simulate pressurized tanks. Both oxidizer and fuel tank were pressurized to 652 psi while the helium tank was pressurized to 9780 psi. It is important to check that the pressure is pointing on the right direction or else the results will not be liable.

Since the tank has 3 components, it is important to attach them prior to running a simulation. Things that are not attached are clearer when a modal is ran. If the nodes align there is a higher chance for loose parts to attach automatically. If this is not the case,



(a) (b)

Figure 37: (a) Force Distribution; (b) Force Nodes

each node must be attached via rigids single node. The material properties for IM7 carbon fiber/CYCOM 5320-1 epoxy resin are as follows:

Elastic Modulus: 8.85 x 10^6 psi

Poisson's ratio: 0.31

Density: 0.0643

Recall that the thicknesses calculated from the Mathcad was different than the dimensions shown in the model section showing the CAD model. Mathcad dimensions were initially used for the first stress analysis. Based on the results obtained, the thicknesses were arranged accordingly until individual tank components reached a stress of approximately 8.13 x 10^4 psi. Originally the stress that the tanks had to withstand was 6.1 x 10^4 psi for a factor of safety of 2. However, the outcome from these margins resulted in a tank heavier than anticipated which meant the missions goal would not be reached. Referring to literature review discussed earlier, it was decided to use a margin of safety of 1.63 to reduce the weight of the tanks.

Helium tank is composed of 3 parts to which each where assigned a thickness of 1.364 inches but post process from the analysis the thickness of the components changed. Top bulkhead of helium became 1.6 inches while the bottom bulkhead changed to 1.5 inches. The cylinder thickness increased to 2.05 inches. It might not seem as much of a difference but any increase in thickness results in an increase of weight which would not be ideal.

The cylinder from the oxidizer tank increased from 0.096to 0.19 inches and the bulkhead decreased to 0.05 inches.

The cylinder from the fuel tank increased from 0.096 to 0.19 inches like the oxidizer tank.

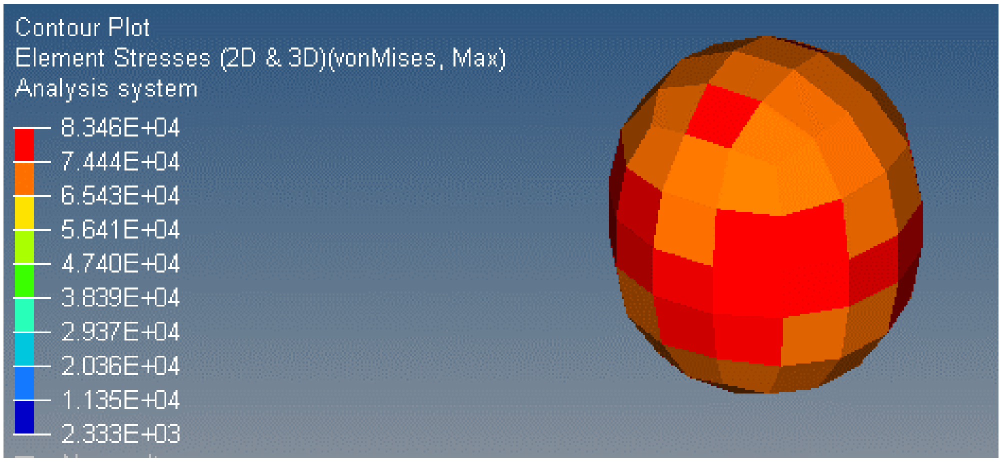


Figure 38: Helium Tank Structural Analysis

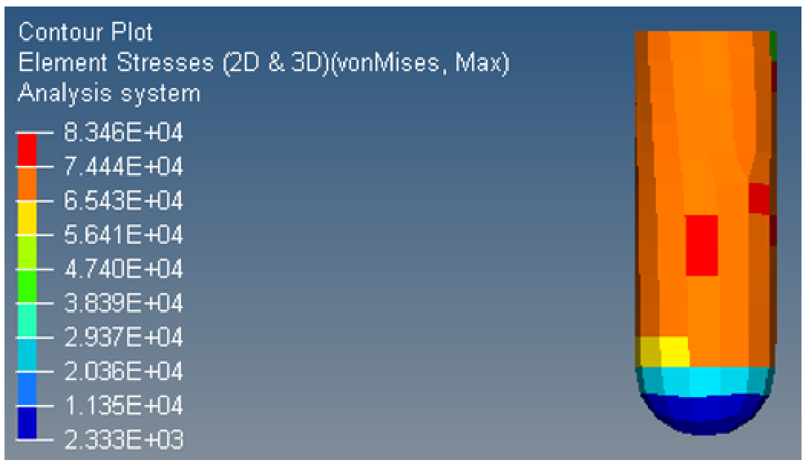


Figure 39: Oxidizer Tank Structural Analysis

The bulkhead of this tank increased to 0.115 inches.

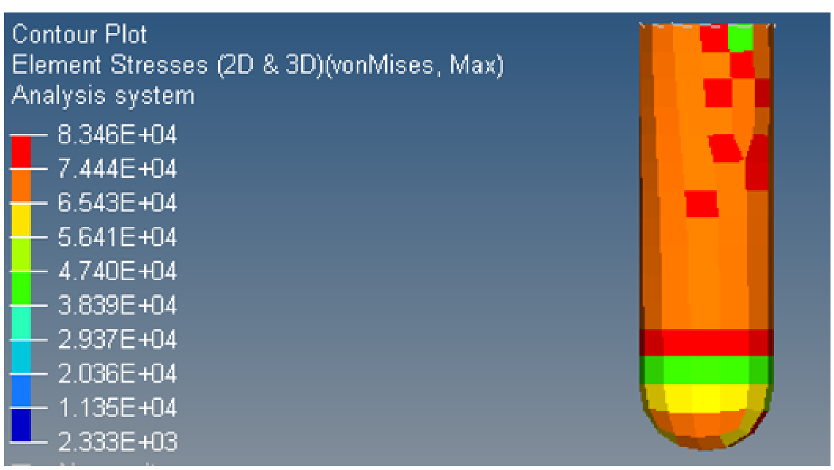


Figure 40: Fuel Tank Structural Analysis

The Helium tank is the only component that is composed by a cylinder and two semi-spheres on both ends. After conducting the analysis, the cylinder has an inner diameter of 45 inches and an outer diameter of 49.1 inches. The upper semi-sphere has an inner radius of 22.5 inches and an outer radius of 24.1 inches while the lower semi-sphere has an outer diameter of 48 inches. The oxidizer tank has a length of 112.656 inches and an inner diameter of 49.1 inches with a thickness of 0.38 inches. The common bulkhead radius is 24.55 and it has a thickness of 0.19. The oxidizer tank will have one inlet and one outlet. The fuel tank has an inner diameter of 49.48 inches and a thickness of 0.38 inches. The common bulk head has a radius of 24.8 and a thickness of 0.23 inches.

Curriculum Vitae

Lucero Buendia is a current graduate student at the University of Texas at El Paso with a focus in structural analysis. As an undergraduate student her research focus was propulsion where she studied the chemical composition and characteristics of a green propellant. She interned at NASA Johnson Space Center during Fall 2017 in the Propulsion & Power Division where she worked with the development of micro-thrusters for a space cube satellite. She received the GEM fellowship (National Consortium for Graduate Degrees for Minorities in Engineering and Science) in 2018 to continue her graduate studies in STEM. Her sponsor is The Aerospace Corporation where she has had the opportunity to intern two consecutive summers (2018 and 2019) in a Structural subdivision- Environments, Test and Assessment. Here she performed modal analysis of numerous SMT leaded parts comparing results from finite-element solutions to close-form equations to develop guidelines for part staking to prevent self-resonant failures. During the summer of 2019 Lucero had the opportunity to participated in NASA's SLS mobile launcher structural analysis of supports from the tower assembly. She is also knowledgeable in assessing the Steinberg method versus finite element analysis through SMT component modeling to adjust factors in the empirical equations to reduce the conservatism of this method. Lucero is very interested in finite element analysis and is constantly learning new software's. Her graduate project focuses in studying the mechanical properties of carbon fiber reinforced polymer (epoxy) composite after exposure to a cryogenic environment. She will become a full-time employee at The Aerospace Corporation upon graduating with her master's degree in science. In her time off, she enjoys weightlifting, study sign language and visit museums.

Permanent address: 13050 Jeremiah Dr.
El Paso, Texas 79928