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Honors Research Projects

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Composite Tie Rod Research, Design and Testing For SAE Baja

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The University of Akron

Senior Honors Research Project

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Introduction and Overview

Composite materials have become increasing popular in recent years. For the Baja SAE team, composites are typically only used for body panels. To grow as a team and to earn additional points in design competition, it was decided to explore composite use in mechanical applications, specifically for the tie rods. Research was conducted, looking into composite materials basics, types, and material properties. Additionally, manufacturing was explored, including a few projects separate from the tie rod application. 3D models were created after the materials were selected, and FEA analysis was conducted on the parts. Once theoretical testing was finished, the physical testing pieces were purchased and assembled, then tested. The most apparent issue with the design was the bond between the selected carbon fiber tubes and manufactured aluminum inserts. This bond, at most was measured at around 45 pounds of tensile force, which is much less than needed in this application, as the carbon fiber was calculated to withstand just over 2,000 pounds. Data was collected and recommendations for additional research and testing were made, including recommendations to attempt to yield better test results. The project, although initial testing yielded disappointing results, is not a lost cause. In the future, additional methods and designs should be explored.

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Part I: Introduction and Background

The Senior Honors Research project is intended to serve as a capstone project for graduating seniors. A senior will choose a project that they are interested in and conduct research in order to further their knowledge within their particular major. This project is focused on composites design and manufacture as a part of the University of Akron SAE (Society of Automotive Engineers) Baja team. This team is given a Briggs and Stratton engine and asked to build an off-road style vehicle to compete against other schools from around the world. This design competition allows students the opportunity to have real world design and manufacturing experience, as well as several other skills such as project management, budgeting, presentations, and many more.

Project Scope

The proposed project was to design and create composite parts for the University of Akron SAE Baja team. Originally, it was proposed that tie rods (part of the vehicle's steering subsystem), camber links (part of the vehicle's suspension subsystem), and a CVT cover (Continuously Variable Transmission Cover for safety purposes) were to be researched for use in the Baja vehicle. Upon further examination of the rules the competition (relevant sections can be found in the appendix), the only components that could be legally made from composites are the tie rods. However, for this project, the testing and research of composites will be applicable for the original proposal, despite not being applicable in a competition setting.

Benefits/Reasons for project

The use of composite materials has several benefits, but the most apparent is that composite materials offer a significant reduction in the weight of a part. Composite materials, specifically carbon fiber and Kevlar fiber products, are known for their high strength compared to their weight. Weight is very important in a competition where vehicles of any kind are being built. For the Baja car, a reduction in weight results in better speed, acceleration, and overall performance. Power to weight ratio is very important with a limited power vehicle such as the Baja car. The lighter the car, the better the car will perform. In addition to being lighter weight, composite materials are often much more cost efficient, however some exceptions do occur, especially with signature composites such as DuPont's Kevlar. Price and weight comparisons will be detailed in the composites design section.

For the composite tie rod application, using a composite material such as carbon fiber has additional benefits. Composite material can have very high tensile strengths. Although composites do not generally perform well in bending, for components such as tie rods, where only tensile and compressive forces are experienced, composite materials can offer many advantages over its steel counterparts.

Definition of Composites

When people think of composite materials, often the first thought is fiberglass or carbon fiber. The term "Composites" actually encompasses a much wider range of materials than many people realize. Composite materials are defined as any material in which two or more materials are combined, usually one being fibrous and the other bonding the fibers in some way, which

have mechanical properties characteristic of both materials. This means that anything from a simple combination of straw and mud to a highly developed material such as carbon fiber can be considered composites.

Composite materials have mechanical properties that are somewhere between the materials that make up the material. One of the best examples of this is concrete reinforced with rebar. Concrete alone is very good in compression, but does not work well in tension. When reinforced with steel rebar, which can take a significant amount of tensile loading, the resulting composite material has intermediate properties of being decent in compression and tension both. This simple and very common example illustrates the fundamental concept behind the idea of using composite materials.

History of Composites

Composite materials have been around for much longer than many people expect. There are records of ancient civilizations utilizing composite technologies to take advantage of the intermediate material properties. For example, the Israelites used bricks in building made of mud and straw. The straw reinforced the mud materials, creating a substance stronger than mud alone, but not quite as strong as straw alone. A more advanced example comes from the Mongolian composite bows in the 11th century in the times of Genghis Khan. They steamed and wrapped a combination of materials, using bonded wood for strength and shape, cattle tendons for flexibility and tensile strength on the tension side of the bow, and horns or hooves for their strength and compression ability on the compression side of the bow. This created one of the strongest and longest lasting bows in history, giving the Mongols a military advantage.

The modern concept of composite materials dates back to 1937 when Fiberglass was first used as reinforcement. Douglas Aircraft noticed that the making of metal molds was impeding the speed of their processes. They found that plastic reinforced with fiberglass was a much faster and effective way of creating molds. The manufacturing of aerospace components was vastly increased with the onset of high product demand during World War II. After the war, the automotive composites market increased significantly. In 1947, the first auto body made of entirely composite materials was made. Composite research continued to improve manufacturing processes. In 1971, DuPont's Kevlar was created, further extending the reach of modern composites.

Today, composites are used in a variety of applications. The chart below illustrates what industries composites are used in today. From aerospace and automotive applications, sports and leisure applications, and even construction applications, composite materials are becoming a very popular material to be used in high performance products.

Figure 1: Uses of Composite Materials
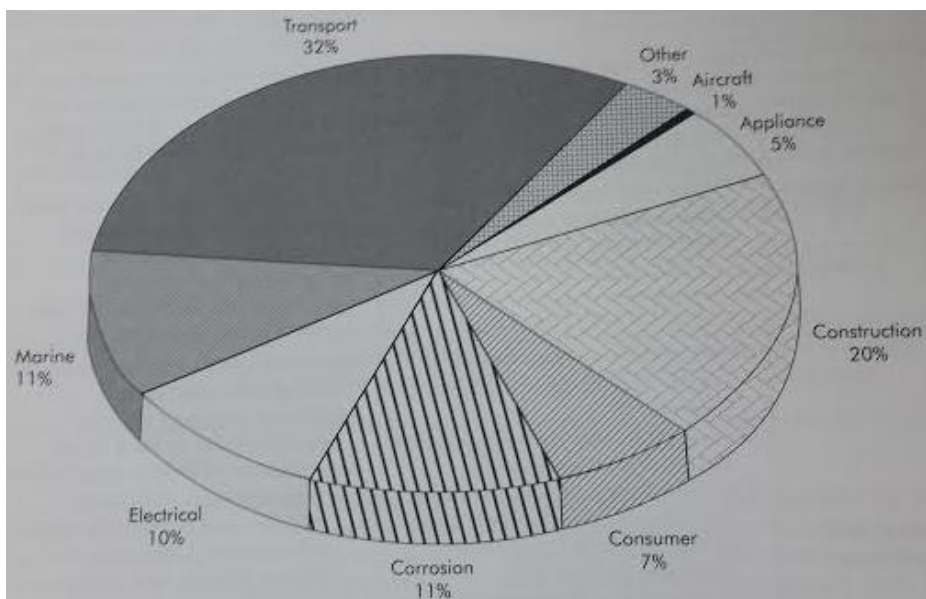
Composites in the Automotive Industry

Composites have been used in automotive applications since the 1950's. With more and more technology being incorporated into a vehicle, weight is greatly increased. In the 1970's, the average mass of a vehicle was around 1600 lbs. In 2010, it has become nearly 3000 lbs. This increase in weight, mostly due to added comfort and safety features, is fairly significant. The use of composites began to be explored as an option to save weight. Now, composites are very common in vehicle design, with some supercars having an entire body created from composite material, usually carbon fiber. This is due to its high strength, light weight, and ability to form shapes and contours that would typically be very difficult. Today, the automobile industry is the second largest consumer of composite products, following the aerospace industry.

Composite Design

The design of composite materials is slightly different than that of a normal material because of the intermediate material properties that composite materials tend to have. The combination of multiple materials adds a level of complexity to determining exact material properties. Many factors impact the properties of a composite material. Composite material mechanical properties are very dependent on the direction of the fibrous material and the different materials used. Curing processes, manufacturing method, and application can also have a significant effect on the properties of a composite material.

Composite Material Components

In a composite material, there are two main components which make up the whole of the material: what is known as the fibrous portion and what is known as the matrix portion. The fibrous portion generally consists of several hundred to several thousand thin filaments, which are bonded together in the matrix portion, which is generally a resin or epoxy, but can also be other materials. With the fibers and the matrix, the composite material comes together to form one single material with intermediate material properties.

Fibers

As stated previously, the fibers are what are held together by the matrix. Fiber composition can be of two types: continuous and discontinuous. Continuous fibers are very long strands of the fiber material which have been manufactured as a single filament. Discontinuous fibers are made up of several smaller portions of material woven together into a filament. Fibers should be as thin as possible. Thin fibers make it

easier to weave the fibers into a sheet. In addition to ease of manufacture, thinner fibers have mechanical advantages over thicker fibers. As the diameter of the fibers increase, the overall rupture strength decreases. In other words, several smaller fibers have more desirable strength than just a few thicker fibers. When fibers are manufactured, the fibers are surface treated to ensure that the size of the fiber is proper and also to decrease the amount of abrasion in the weaving machines. This process also improves the adhesion to the matrix when the composite is being formed and cured into its final form.

There are several materials that can be used as a fiber in a composite material. Some of the most common are glass, Kevlar, carbon, boron, silicon carbide, and high density polyethylene (HDPE). Below are listed some of the manufacturing techniques and properties for the most common of the above listed:

Glass

Glass fibers, which are most commonly made by melting Si, Na_2CO_3, and $CaCO_3$ at temperatures above 1000°C, are made by drawing glass through a heated platinum alloy plate. Composites made with glass reinforcement are commonly referred to as fiberglass, but are also known as glass fiber reinforced plastic (GFRP) or glass reinforced plastic (GRP). Fiberglass was one of the first modern composites to be produced and utilized in industry, although glass fibers have been around as early as ancient Egypt with sculptures, according to one source. Owens Corning is credited with the invention of fiberglass (although their product was known as "fiberglas"). As a jet of compressed

air accidently blew molten glass into a cluster of thin fibers, the beginning concepts of fiberglass were initialized. Today fiberglass is used for its light weight, ease to manufacture, and relative strength. Fiberglass is utilized in industries across the board from boats and skis, to castings and car body panels.

Figure 2: Examples of Fiberglass

(http://www.revampthecamp.com, https://www.frpfittings.com)

Kevlar

Kevlar is a name brand product of DuPont made from poly-paraphenylene terephthalamide. This product, similar to fiberglass, was discovered completely by accident by a woman by the name of Stephanie Kwolek. While researching a type of polymer material, she noticed that the solution of polymer that she was working on appeared cloudy, which was atypical. Intrigued, she studied the material and found that it had incredible strength. This solution of polymers became the stepping stones to creating one of the strongest polymer chains known to man.

Kevlar is made of aramid fibers, which appear yellow in color. These fibers are made of aromatic polyamide, a synthetic material, which is created at temperatures below the freezing point, usually around -10°C. These fibers are then spun and

stretched, which allows for a high modulus of elasticity along the direction of the fibers. Kevlar is most well known for its use in bulletproof vests, but can be used in a variety of applications. It is extremely lightweight and durable. Its strength to weight ratio is around five times that of steel, making it the perfect material for high stress situations.

Figure 3: Kevlar Examples

(http://composite.webs.com,http://www.serendipite-strategique.com)
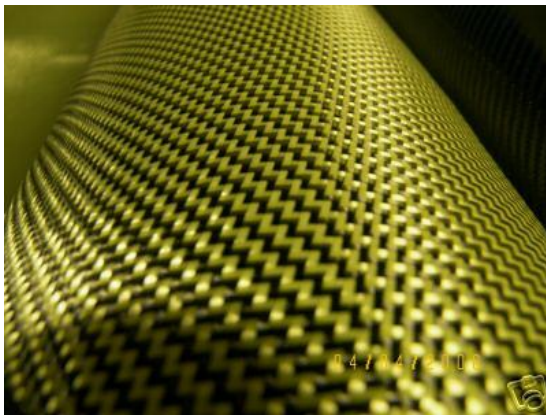
Carbon

Carbon as a fiber in composites most commonly is called carbon fiber, but can also be referred to as carbon fiber reinforced polymer (CFRP), carbon reinforced plastic (CRP), and carbon fiber reinforced thermoplastic (CFRTP). The carbon molecules form in a hexagonal chain to form the fibers. Carbon fiber was first created in 1879 in Cleveland, Ohio. Thomas Edison used carbon as filaments in the streetlights that lined the downtown Cleveland streets. He created these filaments by heating cotton threads until they became carbonized. In 1958, a man by the name of Roger Bacon, also in Cleveland formed his fibers by heating rayon strands. These first carbon fiber products tended to have low percentages of actual carbon and thus had a low tensile strength.

More refined processes can produce carbon fibers that are much stronger. Today, they are typically made from one of two types of materials. The first is a Polyacrylonitrile based or PAN based carbon fiber, which tends to have greater tensile strengths. This is because of the more disconnected structure of the molecules which make up the fibers. The second, pitch based fibers, tend to have a more ordered molecular composition, which gives this type better thermal conductivity. These types of fibers are made from petroleum pitch which is a highly viscous petroleum residue. Pitch is oxidized at temperatures over 300°C. The fibers are then placed in an atmosphere comprised of mostly nitrogen and heated to around 1500°C. Pitch based fibers can be composed of up to 85% carbon, almost 30% greater than that of PAN based fibers, but due to the molecular structure, the properties are not nearly as desirable as those of PAN based fibers. However, through manipulation of the fibers as they are being formed, experimental research has shown that pitch based fibers can yield greater tensile properties. Carbon fiber composites have been well known for their use in the automotive and aerospace industries.

Figure 4: Carbon Fiber Examples

(http://www.macyindustries.com, https://encrypted-tbn3.gstatic.com)
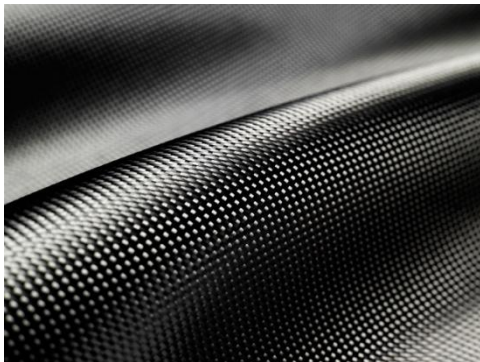
Matrix

The matrix, as stated previously, is generally a resin or epoxy. Several types of matrix have been known to be used including thermoplastic resins, thermoset resins, minerals or ceramics, or even metals. Each type of matrix yields different properties when used in combination with different fibers. Many properties of a composite are determined by the matrix. Shown below is a table of various matrix properties. Some environmental means affect the matrix in different ways. For example, heat can cause some resins to melt or soften. Also, some polymer matrices react with solvents or stains. Some common matrix materials and their descriptions are listed below:

Polymeric

Polymer matrix composites (PMCs) are plastics and resins which are categorized as thermoplastic resins or thermoset resins. A resin becomes a plastic through forming, molding, or curing. Most resins are liquids, but some can be solids which are first heated in order to be melted down. The difference between a thermoplastic resin and a thermoset resin is that a thermoplastic resin can be heated (usually around 300°C) and formed multiple times. Examples of thermoplastic resins are polyesters and polyethylene. A thermoset resin is generally a liquid, which, once it becomes a solid, cannot return to its liquid state. Beginning as a low viscosity liquid, thermoset resins cure either by time, heat addition, or both. Curing is the process which aligns the molecules in the liquid into a solid chain structure. Simply put, using a thermoplastic resin is a reversible process and using a thermoset resin is irreversible.

Ceramic

Ceramic matrix composites (CMCs) are used primarily to increase a materials toughness. Ceramics can tolerate significantly higher temperatures, be as strong as, and are much lighter than many metals. Generally, with a ceramic matrix, ceramic fibers are used, but other fibers such as aluminum and carbon have also been known to be used with a ceramic matrix. CMCs are perfect for applications where the material must withstand a significant amount of heat. Heat shields on rockets, some brake discs, and furnace linings are a few examples of CMC applications.

Metallic

Metal matrix composites (MMCs) provide for very strong materials with a slightly different set of properties than those with resin matrices. A metal matrix is generally a lighter weight metal such as aluminum, though most metals and alloys can be used. Most often, ceramic fibers such as silicon carbide and aluminum oxide are used with a metal matrix due to their heat resistance. To use metal as a matrix, the metal is often melted and poured over a sheet of woven fibers. Other fiber materials commonly used with a metal matrix include carbon and silicon carbide. Another manufacturing technique is to use physical vapor deposition, more commonly known as PVD. In this process, the fibers are placed in an argon rich atmosphere, along with bar stock of the metal which is to be adhered to the fibers. A negative charge is carried across the material and either an electron beam or electric arcs cause the vaporized metal to adhere to the fibers, creating a very thin coating.

There are several advantages to using metal as a matrix for certain applications. They tend to be fire resistant, better conduct heat or electricity, and do not absorb moisture. Because metal is fairly good in load bearing situations, the reinforcement in MMCs generally is used to prevent deformation in the matrix. Fibers also serve to increase the overall strength and stiffness of the MMC as well as reduce the total density. A few common examples of MMCs are carbide drills, some automotive disc brakes, and some airplane landing gears.

Composite Fabric Weaves

Fibrous reinforcements are generally produced as single filaments. These filaments are typically very thin and fragile and have a tendency to break. For this reason, filaments are spun together to create strands, which are also known sometimes as fibers (Fiber is a general term which is often used interchangeably for both strands and filaments). The composite material known as fiberglass has a special name for strands. A single strand of fiberglass is referred to as a roving. For most other materials, a single strand is referred to as a tow, but the common term strand is often used rather than the specific terms. Several strands of a material can be spun together to make a yarn. This is typically the largest a particular group of filaments will get.

Weaves can come in one of four basic forms: Unidimensional, Bidimensional, Tridimensional, and Multidimensional. Unidimensional weaves have fibers which are oriented parallel to each other in a single direction. Bidimensional weaves have fibers oriented in two directions, usually perpendicular to each other. Tridimensional weaves have three separate

fiber directions. Multidimensional weaves have more than three fiber directions. The basic form of each is shown in the below figure.

Figure 5: Weave Forms
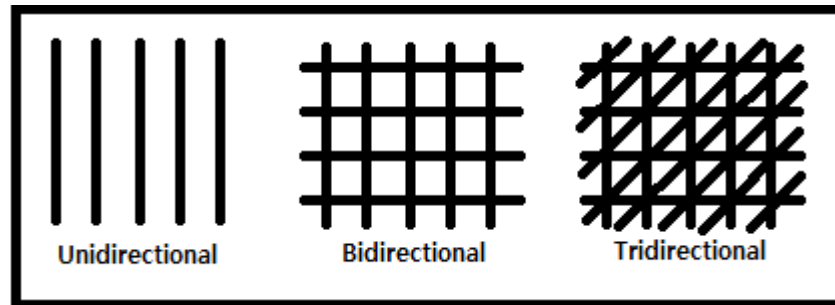
Most commonly, weaves are bidirectional, but tri or multidirectional are used on occasion. For bidirectional weaves, there are the two main directions of the fibers known as the wrap direction and the fill direction. Weaves can be characterized by the amount of space between the fibers commonly referred to as openness, and by the fabrics ability to conform to a particular shape, which is known as drape.

Several of the most common types of weaves will be detailed below including plain weaves, basket weaves, twill weaves, satin weaves (also known as harness weaves), crowfoot weaves, leno weaves, triaxial weaves, and weft knitting. Pictured in the below figure are the plain, basket, twill, satin, crowfoot, and leno weaves.

a. Plain weave

b. Basket weave

c. Twill weave

d. Satin or harness weave (8 end)

e. Crowfoot weave (3 and 4 end)

f. Leno weave
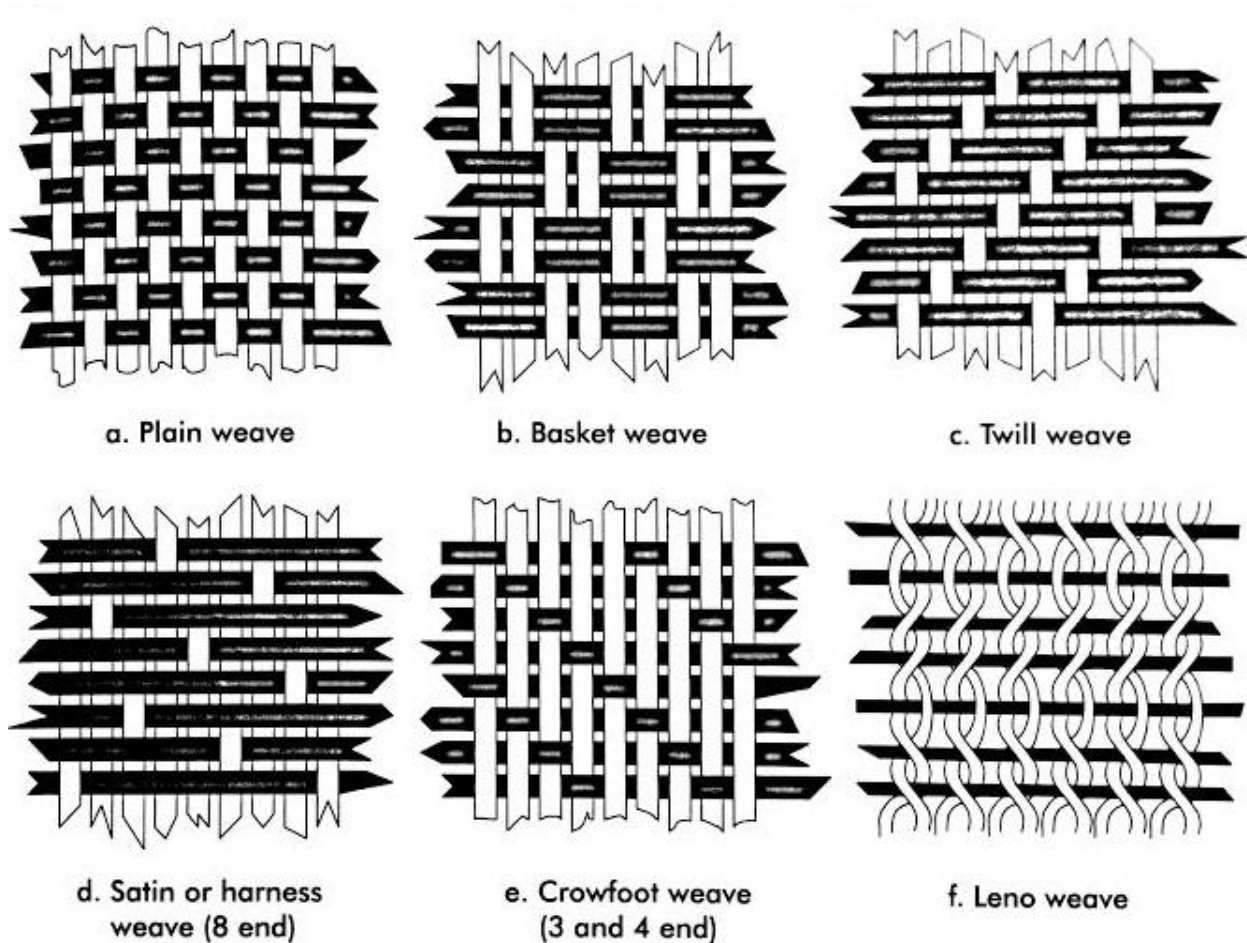
(from *Fundamentals of Composites Manufacturing Materials, Methods, and Applications*)

Plain Weaves

The plain weave is a type of bidirectional weave which follows an under-over pattern. One set of parallel fibers are oriented perpendicular to another set. This weave is generally very stiff and has equal strength in both directions. To maximize the amount of fill from the matrix, this weave is typically left very open. Plain weaves are good for flat applications, as they do not drape as well as other weaves because of the high number of crosses between the weaves.

Basket Weaves

The basket weave is also a bidirectional weave which follows the "over two, under two" pattern. The first parallel set of fibers is perpendicular to a second set. This weave drapes better than the plane weave, but is not nearly as stiff. This weave is flatter and stronger due to the fewer number of crosspoints, or crimp points.

Twill Weaves

A twill weave is a bidirectional weave type which has the pattern of three fibers in the wrap direction woven under one fiber in the fill direction. This weave type is much more flat and stronger that other weave types because it has fewer crosspoints or crimp points. Having fewer crosspoints also reduces the amount of defects in the weave. Twill weaves are very popular, especially with carbon fiber and aramid fiber composites.

Satin/Harness Weaves

The satin harness weave is also a bidirectioinal weave like the twill, basket, and plain weaves. The most common weave pattern is three strands in the wrap direction and one in the fill, then two in the wrap direction and one in the fill, as shown in the figure above. Other weave patterns are also seen, where the number of strands in the wrap direction is increased. These are named 4-harness, 5-harness and so on. Because of the high number of fibers in the wrap direction compared to the fill direction, this weave is very flat. The higher the number of strands in the wrap direction, the flatter the weave is and the less crosspoints there are, thus making lay up somewhat difficult. The weave has a very high drape so it conforms easily to whatever shape is desired, but it is very difficult to orient the fibers for optimal strength. The weave is commonly left to

be less open and a vacuum is often used to eliminate air from the material. This type of weave is often used in aircraft, but is also common in composite houses.

Crow Foot Weave

This weave, again bidirectional, is actually a form of satin weave. The difference is that the stagger pattern is not necessarily repeated in a pattern. This weave has high strength in the wrap direction, high drape, and a high strand count. This weave is often seen in fishing poles, diving boards and skis, but has the potential to be draped over something as curved as a sphere.

Leno Weave

The leno weave is a somewhat different type of weave in which two strands in the fill direction are intertwined around a single strand in the wrap direction in a braided fashion. Leno weaves are rarely used alone, but rather used in conjunction with another weave type as a core. The weave is very open, but is not very flat due to the many thick crosspoints caused by the locking braid. Although the weave has many crosspoints, drape is not affected and is still high due to the openness of the fabric. Strength is reduced in this weave type, but it allows for several thick plies, which reduces the amount of lay-up time.

Weft Knitting

Weft knitting is very similar to a knit that would be used in the textile industry. This weave type is very flexible and stretches well. It has very high drape and conforms

well to any mold. The most important property of a knitted weave is that it transfers energy very well.

Ply

Ply is defined as a single layer of laminated material. When working with composites, several layers are often used to increase strength and thickness of the material. These layers are referred to as plies. Plies can be formed together and cured together, or even cured separately and bonded together by epoxy. The more plies a part has, the thicker the material is. Strength and toughness are increased with each additional ply, but weight and material cost are also increased. For some applications, the additional strength received from additional plies is worth the extra weight and expense. Additional plies do however, allow composites to be used in a wider variety of applications due to the increased strength.

Plies, like weaves, can be unidirectional or bidirectional. Layering plies in multiple directions increases the strength in multiple directions. Unidirectional plies increase the strength in a single direction. Ply orientation is very important to the composites performance and must be considered in design.

Advantages of Composite Use

Composite materials have many benefits over traditional materials, but the most apparent is that the uses of composite materials provide a significant reduction in weight. Weight reduction in vehicles translates to fuel savings, an increase in payload capacity, and an increase in fuel range, to name a few. Composite materials are also resistant to fatigue failure, unlike many traditional materials. This increases the overall life of the part and leads directly to

cost savings in maintenance, inspections, and replacement parts. In addition to being resistant to fatigue, composites are very resistant to corrosion.

Composite materials, compared to metals are typically less expensive. Compared to steels, carbon fiber, for example, is almost half the weight and more than half the cost. A table outlining some cost comparisons and additional comparisons including strength and manufacturing processes can be seen below.

Table 1: Composites Compared to Other Materials

Table 1.1 Some Significant Cases

Application	Previous Construction	Composite Construction
65 m³ reservoir for chemicals	Stainless steel + installation: Price = 1	Price = 0.53
Smoke stack for chemical plant	Steel: Price = 1	Price = 0.51
Nitric acid vapor washer	Stainless steel: Price = 1	Price = 0.33
Helicopter stabilizer	Light alloys + steel: Mass = 16 kg; Price = 1	Carbon/epoxy: Mass = 9 kg; Price = 0.45
Support for helicopter hoist	Welded steel: Mass = 16 kg; Price = 1	Carbon/epoxy: Mass = 11 kg; Price = 1.2
Helicopter motor hub	Mass = 1; Price = 1	Carbon/Kevlar/epoxy: Mass = 0.8; Price = 0.4
X–Y table for fabrication of integrated circuits	Cast aluminum: Rate of fabrication = 30 plates/h	Carbon/epoxy honeycomb sandwich: Rate of fabrication = 55 plates/h
Drum for drawing plotter	Drawing speed = 15–30 cm/s	Kevlar/epoxy, 40–80 cm/s
Head of welding robot	Aluminum: Mass = 6 kg	Carbon/epoxy: Mass = 3 kg
Projectile for loom	Aluminum: Rate = 250 shots/min	Carbon/epoxy: Rate = 350 shots/min
Aircraft floor	Mass = 1; Price = 1	Carbon/Kevlar/epoxy: Mass = 0.8; Price = 1.7

(from "Composite Materials Design and Application" by Daniel Gay)

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Composite materials are becoming increasingly popular in industry not only for their price, strength, and weight, but also for ease of manufacture. Considering the above table once again, specifically the case for "X-Y table for fabrication of integrated circuits", the table shows that 55 could be made from composites in the time that it would take to make 30 from cast aluminum. The biggest factor that limits composite manufacture is cure time. Additionally, composites can be formed into many shapes that would be difficult to achieve in other mediums. Curved surfaces, tight radii, and sharp corners are all made simple through the use of composites.

Disadvantages of Composite Use

The main disadvantage of composite use is that the failure is fairly catastrophic. Specifically, the failure called delamination, which is the shearing of ply from ply or fibers from matrix, can cause serious problems, especially when used in tie rod application. If delamination were to occur, most likely near the insert where the highest forces are seen, the loss of steering capabilities would be lost. In a race such as the endurance race, this can cause other components to be damaged due to the nature of the race. Other disadvantages include a loss of strength in bending. Because most composites being used have a polymeric matrix, the tendency to experience bending failure is greatly increased as compared to steel or aluminum. Tie rods, which ideally experience only tensile and compressive forces, reduce the risk of bending failures, but accidents still occur. With weight and cost reductions, it is no mystery that composites have been becoming increasingly popular in recent years.

(From http://www.tenerife-training.net/Images/Delaminated-Head-Tube-Failure.jpg)

Composite Manufacturing

The manufacturing process of composite materials is slightly different than most techniques for metal forming and is actually more closely related to plastics manufacturing techniques, depending on what type of fibers and matrix are used. There are several common techniques, but the most common involve the use of a mold of one form or another.

Molding

The manufacturing processes for composite materials are sometimes unique, due to the hybrid nature of the materials. In order to form composite materials into the desired shape, a mold is often used, especially with polymer or metal matrix composites. Molding, often referred to as "lay-up," is often a lengthy process, but can be made easier and quicker through the use of a variety of tools. There are many different molding strategies and types. The most common will be detailed below.

Types

There are several techniques for composite molding, most of which fall into the category of either open molding or closed molding. Open molding uses a single mold. The composite's fiber material is either laid over top of, or within the mold, and the matrix added to create the solid composite material.

Closed composite molding uses a pair of molds. The mold is placed, the composite fibers and matrix are fixed over or in the mold, and a second mold is placed over top, sandwiching the composite material in between the two molds.

Beyond open and closed types, molding types are further categorized into manual processes, compression-based processes, injection processes, and continuous processes. The following, contact molding, compression molding, vacuum molding, and resin injection molding are a few common examples of both open and closed molding types.

Contact Molding

Generally used with thermoset resins, contact molding is a manual method of open molding which involves placing fibers on a mold and impregnating the fibers with resin, usually in combination with an accelerator, which helps decrease the time required for curing. A roller or a vacuum is used to remove all air from the composite material prior to full setting.

Figure 8: Contact Molding
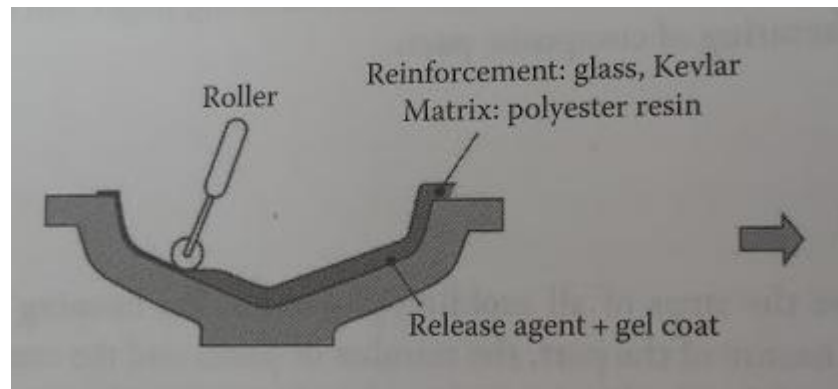
(from "Composite Materials Design and Application" by Daniel Gay)

Compression Molding

Compression molding is a type of closed molding which uses a mold and what is known as a counter mold to apply a slight compressive force on the composite material.

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Compression molding, as the name would suggest, is a type of compressive processing. One to two bars of force are applied to the mold, either by the weight of the counter mold alone or added force provided mechanically by an outside force or, more simply, by using weights.
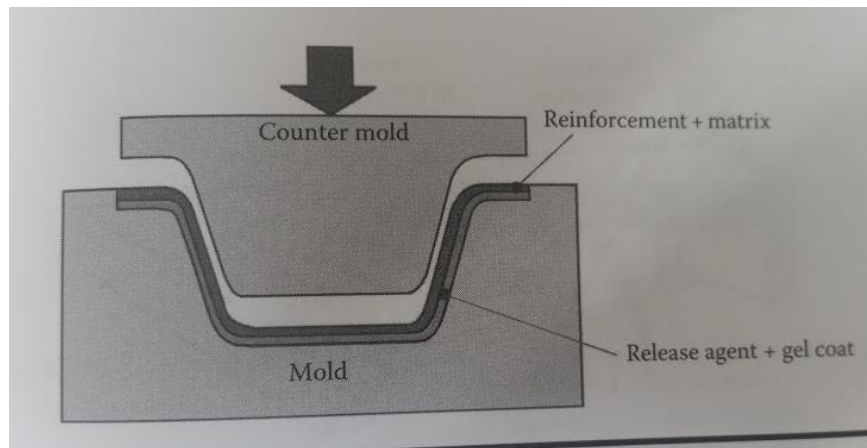
(From "Composite Materials Design and Application" by Daniel Gay)

Vacuum Molding

Vacuum molding is also referred to as depression or bag molding and is categorized as a type of compression molding. It is a type of open molding that has a wide variety of applications, including small radii and curves. The fibers are laid over the mold and a vacuum bag placed over the composite after the matrix material is added. By removing air from the bag over the composite material, the atmospheric pressure is the force that is applied on the material.
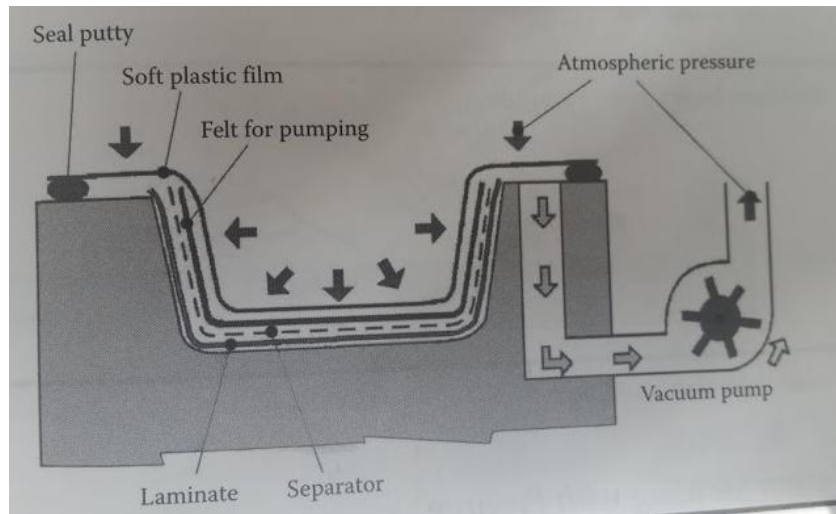
(from "Composite Materials Design and Applications" by Daniel Gay)

Resin Injection Molding

Resin Injection molding is a type of closed molding where the resin is injected through the molds into the composite fibers. This process can be automated, which is why it is a very common composite molding type. The process is very similar to that of plastic injection molding.

Figure 11: Resin Injection Molding

(from "Composite Materials Design and Application" by Daniel Gay)

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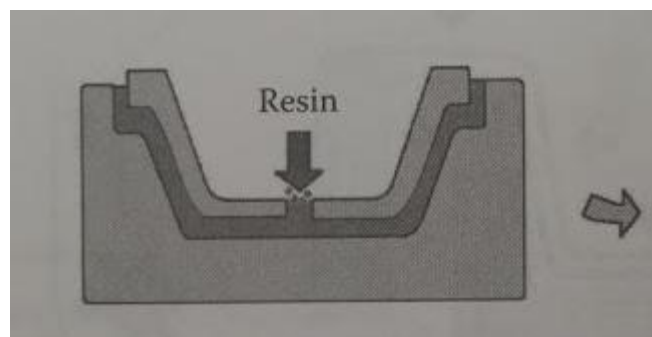
Other

Other less common manufacture types include:

- Electron Beam/X-ray Molding
- Foam Injection
- Pultrusion
- Centrifugal Molding
- Sheet Forming
- Stamping
- Filament Winding
- 3-D assembly

Tie Rod Design

Tie Rods are a very important component in a vehicle's steering system. They connect the steering rack to the tires, which allow the driver to change the direction of the tires. Tie rods are typically made of steel, but can be made of other materials with careful and thoughtful design. Composites are not common, but have been used in tie rod design. The biggest concern for composite use in tie rod design for the Baja team comes from the unexpected nature of the Baja endurance event.

SAE Baja Competition

Before getting into the specifics of design, it is important to understand the Baja team purpose and competition. Baja teams across the country and even across the world are given a Briggs and Stratton Engine for use in a competition sponsored and put together by the Society of Automotive Engineers (SAE). This competition is designed to put students' engineering skills to the test in a variety of events for their car to compete in. Each year, the University of Akron sends their Baja team to competitions across the country, competing with hundreds of teams from across the world.

The Baja competition consists of two types of events. The static events are events that do not involve moving the vehicle. Dynamic events are where the vehicle is both moving and often tackling obstacles. Before a vehicle can compete, it must pass a technical inspection. Rules for competition and design are outlined in the 2015 SAE Baja rules. At technical inspection, often referred to tech inspection, or simply tech, the car is scrutinized, ensuring that all rules have been followed and the vehicle is safe for competition. Teams often do not pass

the first time through, so last minute changes and engineering must sometimes be performed in order to pass. Once tech is passed, the vehicle must pass a break test before it can compete. This test requires the driver to bring the Baja car to full speed and rapidly slam on the breaks, causing all four tires to lock up. If all tires lock up, the vehicle is passed for dynamic events.

Static events can be completed without having passed technical inspection. These events include the cost event, the design event, and the marketing event. The cost report is a report which must be submitted prior to competition. It details every component of the vehicle and requires proof of costs, cost adjustments based on the SAE given adjustment scale, and lists of fasteners used. The cost event is scored by awarding points based on the total cost of manufacturing the vehicle. Less expensive vehicles will generally receive more points than more expensive vehicles. The design event is performed by a panel of judges. The judges will speak with each design leader, scrutinizing design choices and innovation. Teams that score well in design often have design which are innovative and well thought out. Extensive testing is also looked highly upon when awarding design points. Finally, the marketing presentation focuses on a scenario where members of the team are to create a sales pitch, highlighting the strengths of the vehicle. Points for this event are awarded based on the sales pitch itself, financial analysis, and preparation.

Dynamic events are events where the vehicle is in motion. These include the acceleration event, hill climb/traction event, maneuverability event, suspension event, and endurance event. These events require that a vehicle has passed technical inspection before competing and are scored based on fastest times. The acceleration event measures the

acceleration capabilities of the vehicle by timing the fastest run over a specific distance. The hill climb or traction event, maneuverability event, and suspension event test each of those subsystems, again timing for the fastest run time. The endurance event is slightly different and is by far worth the most points of any event. This race is four hours in duration and consists of several obstacles, designed to beat and wear on the vehicles over time. The teams with the most laps at the end of four hours receive the most points. After all events are completed, the scores are added together and the winners are announced.

Baja Steering System

For the University of Akron Baja vehicle, the steering system is fairly simple. Major components include the steering wheel, the steering column, the steering rack, tie rods, rod ends, the uprights, and the tires. The assembly, modeled by the steering subsystem of the University of Akron Baja team can be seen below. A full table of steering specifications can be found in the appendix.

The steering subsystem works through driver input. The driver of the vehicle turns the steering wheel, which turns the steering column. The steering column interfaces with the rack, which transmits the rotational motion originating from driver input into lateral motion. This lateral motion is transferred through the tie rods and creates a moment on the uprights. This moment is what causes the wheels to turn, which allows for the driver to steer the vehicle.

The steering subsystem requires two tie rods, one for each wheel. Each of the tie rods in the original design are made of 4130 Chromoly Steel and weighs approximately 0.57 lbs per tie rod assembly. By replacing the steel tie rods with carbon fiber, the weight can be reduced nearly by nearly 50%, weighing only 0.297 lbs. The majority of this weight comes from the aluminum inserts required for the attachment of other hardware.

As stated before, weight is very important for applications such as racing. Although it may not seem like much, saving weight anywhere possible is important. Using composites for the tie rods will also allow for potentially a higher score in the design event.

Mathematical Model and Governing Equations

Referring to Dr Gross's chapter on steering in his Vehicle Dynamics course, several equations can be used to estimate the forces that the tie rods may encounter during the Baja races. From the steel tie rod calculations, the axial force of the tie rod used is 75.61 pounds which yields a compressive force of 480.8 psi. This force, which acts on the steering arm, is denoted by F in the below figure, borrowed from Dr Gross's Steering chapter.

Figure 13: Steering Arm Free Body Diagram
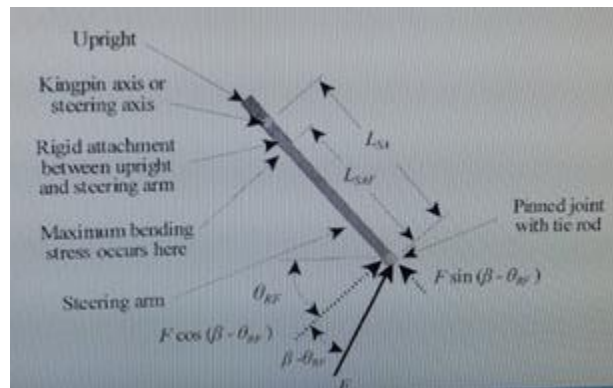
To calculate the critical force in a tie rod, the following equation is used:

$$F_{crit} = \frac{\pi^2 E_{tr} l_{tr}}{L_{tr}^2}$$

For the Elastic Modulus, steel is around 29,000 ksi whereas carbon fiber is around 16,000. To complete this calculation, l_{tr} must be determined using the following equation:

$$l_{tr} = \frac{\pi(D_0^2 - D_i^2)}{64}$$

$$l_{tr} = \frac{\pi(0.75^4 \, in - 0.68^4 in)}{64} = 0.0027 \, in^4$$

These values are the same as the steel calculations performed by the steering subsystem lead. The critical force is slightly different due to the difference in material.

$$F_{crit} = \frac{\pi^2 * 16 \, psi * 10^6 * 0.0027 \, in^4}{14.27^2 in}$$

For steel, F_{crit} is equal to 3884 pounds. For carbon fiber, that value can be compared to a value of 2093.80 pounds.

Part II: Modeling, Testing, and Final Design

Initial Research and Information Gathering

Carbon Fiber Products

There are several options when it comes to purchasing carbon fiber. Carbon fiber can be purchased in rolls of cloth with no resin and prepreg (which is short for pre-impregnated carbon fiber) for techniques requiring molding or lay-up. Sheets of flat carbon fiber which has already been introduced into the matrix can be purchased, but this does not allow for shaping or forming of the material. Tubes or rods of many different shapes or sizes can also be purchased. For tie rod application, purchased tubes are the option which was chosen due to the complex geometry, in terms of lay-up, and inexpensiveness of the product.

For purchased carbon fiber rods or tubes, the products generally come in one of two types; Pultruded, which has fibers along the axis of the tube, and roll-wrapped, which has fibers that are wrapped around the circumference of the tube. Due to time and resources, the option of laying up carbon fiber was not explored. This decision also allows for strength and other properties to be relatively uniform as opposed to attempting the difficult task of laying up and aligning the carbon fibers on a very small radius.

SAE Baja Discussion Boards

Extensive reading and studying of the Baja and even Formula SAE boards was done in order to see what has worked and what might have failed for other teams. Few teams have

attempted to pioneer the use of composites in design other than in the body panels. From research into composite tie rod design, the most common failure was not in the composite material and not in the inserts, but in the bond between the aluminum (or steel in a few cases) and the composite material.

Material choices varied, but many teams that were using composites in tie rod design chose to use a Kevlar tube rather than carbon fiber. The trend seemed to be based solely on its superior tensile strength. Adhesion properties of Kevlar vs. Carbon Fiber were not discussed extensively, and could possibly be tested in the future. Teams that used carbon fiber over Kevlar mainly seemed to do so due to cost restrictions. Carbon fiber rods tend to cost around $25 each, whereas Kevlar rods tend to cost anywhere from $60 to $150 each and are much harder to come by. Although Kevlar is stronger in tension, carbon fiber is significantly cheaper, especially when it comes to tubes. This affects both the team budget and the cost report which is to be submitted to the judges before competition.

Lay-up Techniques

Although it was decided that the carbon fiber rods would be purchased, it is important to understand the process of manufacturing composite materials with limited technology. The following are a few of the most applicable techniques used at the student level, due to their simplicity and low cost.

Simple Method: Baja Competition "Emergency" Lay-up

This year with the Baja team, an emergency lay-up was required at competition. Due to a rules change from year to year, it was required that the plastic seat be replaced with one that

was either composites or metal. Without the resources to create a metal seat in the amount of time there was left to pass tech, the team was forced to make the decision to take the original plastic seat and cover it with fiberglass to create a composite material. From Lowe's, 3M fiberglass cloth was purchased along with appropriate epoxy and hardener.

Figure 14: Fiberglass Cloth

(from Lowe's website, http://www.Lowes.com)

The fiberglass cloth was laid over top of the original seat and cut to size. Resin was mixed in a mixing container and poured over the fiberglass cloth. Paint brushes were used to smooth the cloth over the contours of the seat and to remove any air bubbles, which can make the final product brittle. The following set of pictures depicts the process below:

After the seat was successfully covered in fiberglass, it was allowed to cure overnight to allow the resin sufficient time to harden. Fiberglass requires a significant amount of surface treatment after hardening. A power sander was used to create a smooth, comfortable surface for the seat. After the surface has been treated and the required holes re-drilled, the seat cover was fitted over the seat again and the new composite seat passed technical inspection.

From this process, a few important things about the lay-up process were discovered. First of all, using excess hardener may decrease the curing time for the resin, but risks losing large amounts of resin that is unused in the mixing container. From this also, it was discovered that large amounts of resin and hardener cure faster than smaller amounts. If the resin is spread out, it will be liquid longer than liquid left in the mixing container. A photograph of a container of lost resin due to this unexpected characteristic is shown below:

Figure 16: Hardened Resin Removed from Mixing Container

Through this very simple method of lay-up, using just the plastic seat as an open style mold with no vacuum bags or pressure used, a rough version of the shape can be made quickly. Although it might not be aesthetically pleasing, the method used was perfect for an object such as the seat, which would be covered by the seat cover and would not be visible.

Another Student Lay-up Method (From Previous Experience)

As an additional example of previous lay-up experience, for the FSAE Electric team last year the body panels were made from fiberglass. For the nose cone, no specific shape was defined other than needing to fit over top of the impact attenuator, so a foam mold was used. The purpose of this device is to deflect the impact in a crash situation. It is intended to protect the driver, as well as the overall structure of the vehicle. The mold was made from pink Owens Corning Foamular foam which was cut and sanded to the desired shape. Other mold techniques use wood to create a more permanent mold of the part.

Figure 17: Foam Molds of the Nose Cone
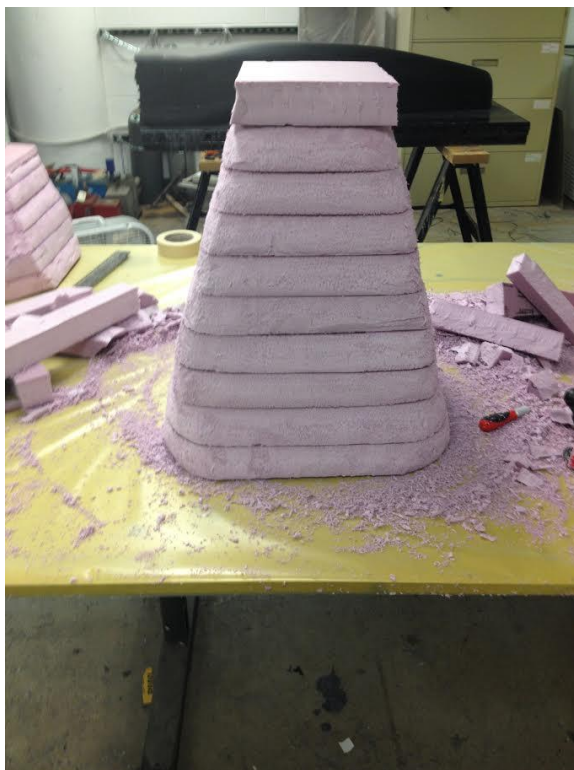
What separates this method from the previous method is that sheets of heat shrink were draped over the foam mold and heated to create a smooth surface on the foam. This also

prevents the foam mold from dissolving when the epoxy matrix was added to the fibers. After a smooth surface was created, the fiberglass cloth could be draped over the mold. Epoxy was added to the mixture and the cloth was made to have no air bubbles before being placed in a vacuum bag. This technique was open molded, but a top mold could have been used in combination with the vacuum in order to seal and add pressure, which ensures that all air is removed from the process.

The finished part was left to cure for 24 hours, after which it was cut from the mold and sanded vigorously by hand. Many other students utilize the use of a power sander; however the Electric team did not have access to one and did not have the budget to purchase one. A dust collector along with proper personal protective equipment (PPE) was used to prevent the inhalation of glass fibers, which can be dangerous with prolonged exposure. Once the fiberglass composite was sanded to a smooth finish, the finished nose cone was painted with spray paint in order to give it better aesthetics. The finished product is pictured below.

Other formation methods can include expensive molds or treatment of the composite during curing. These methods were not explored due to limited resources, including cost. Large molds can be very expensive. Molds can be made by hand, but time did not allow for such a project, especially for something as small and complex as a carbon fiber tube.

Molding Choices

Although the lay-up method allows for the designer to have complete control over the shape of the part, for carbon fiber tubes, the best option is to purchase the parts. With little lay-up experience and the possibility of misaligning fibers, which could greatly affect the tensile strength of the part, professionally manufactured parts are the easiest way to ensure a perfect rod and will minimize imperfections in the design, therefore minimizing risk of unwanted failure.

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Composite Type Comparisons

With a wide variety of composite types, both for the fibers and the matrix, each potential product was analyzed, keeping the desired application in mind. Some of the things that were considered were weight, tensile strength, and cost to name a few. Composite materials have a wide range of material properties and applications so there were many options to consider.

Data Collection

Research yielded several charts for both fiber types and matrix types were, which helps to determine what type of composite material would be best for this particular application. In addition to type of composite, the weave types were also considered. Many sources stated that the weave can make or break a particular composite part. This is because of the orientation of fibers, which generally reinforce the matrix and carry a majority of the load. Certain fiber orientations are better for certain applications. Refer to the weave types section for specific applications for each weave type.

Composite Types and Tables of Comparisons

The following charts outline the differences of several types of matrix and fiber, from a few different sources. From the data, plus data gathered about pricing, it seems that carbon fibers, which are typically paired with a polymeric matrix of one form or another, are the best choice for this particular application.

Table 2: Matrix Types and Properties

Table 2–1. Properties of various matrix materials (non–reinforced).

Property	Polyesters	Epoxies	Polyimides	Phenolics	Thermoplastics	Ceramics	Metals
Maximum use temperature, °F (°C)	175–285 (79–141)	200–350 (93–177)	400–600 (204–316)	300–400 (149–204)	340–450 (171–232)	1,500–4,000 (815–2,204)	1,000–2,000 (538–1,093)
Flexural strength, ksi (MPa)	8–23 (55–159)	45–55 (310–379)	15–25 (103–172)	7–14 (48–96)	14–18 (96–124)	6–10 (41–69)	—
Flexural modulus, Msi (GPa)	.5–.6 (0.3–0.4)	2.0–2.4 (1.4–1.7)	.5–.8 (0.3–0.6)	1.0–1.2 (0.7–0.8)	.4–.5 (0.3–0.4)	—	—
Density (g/cc)	1.1–1.2	1.2–1.25	1.3–1.4	1.3–1.4	1.1–1.2	1.8–2.5	2.0–6.0
Tensile strength, ksi (MPa)	3–13 (21–89)	5–15 (34–103)	6–13 (41–89)	5–9 (34–62)	5–20 (34–138)	4–20 (28–138)	7–70 (48–482)
Tensile modulus, Msi (GPa)	.3–.6 (0.2–0.4)	.6–.7 (0.4–0.5)	.5–.6 (0.3–0.4)	.8–1.7 (0.6–1.2)	.3–.7 (0.2–0.5)	.5–17 (0.3–12)	7–70 (5–50)
Izod impact, ft–lb/in. (kJ/m)	.2–.4 (3.2–6.4)	.2–.3 (3.2–4.8)	1.0–1.5 (16.0–24.0)	.2–.6 (3.0–9.6)	.4–1.3 (6.4–21.0)	<1 (<16.0)	1.5–2.2 (24.0–35.8)
Moisture absorption, %	0.15–0.60	0.1–0.7	1.1–1.2	—	0.01–0.3	—	—
Elongation, %	1.4–4.0	—	1.1	0.5–0.8	—	—	—
Coefficient of thermal expansion (× 10⁻⁵)	—	6–7	3–5	3–5	3–5	0.5–0.6	0.6–1.2

(From "Fundamentals of Composite Manufacturing")

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Table 6.3. Comparison of selected high performance fibers [1, 3]

Fiber type	Density (g/cc)	Strength [gpd (GPa)^a]	Elongation (%)	Modulus [gpd(GPa)^a]	Specific strength (10^6 in)^b	Specific modulus (10^8 in)^c	Fiber diameter (μm)	Maximum use temperature (°C)
Kevlar 29	1.43	23 (2.9)	3.6	550 (70)	8.8	2.1	12	250
Kevlar 49	1.45	23 (2.9)	2.8	950 (135)	8.8	3.6	12	250
Kevlar 119	1.44	24 (3.1)	4.4	430 (55)	9.2	1.6	12	250
Kevlar 129	1.45	26.5 (3.4)	3.3	780 (99)	10.1	3	12	250
Kevlar 149	1.47	18 (2.3)	1.5	1100 (143)	6.9	4.2	12	250
Nomex	1.38	5 (0.6)	22	140 (17)	1.9	0.5		250
Technora	1.39	27 (3.3)	4.3	570 (70)	10.3	2.2	12	250
Ekonel	1.4	31 (3.8)	2.6	1100 (136)	11.8	4.2		150
Vectran	1.47	25 (3.2)		700 (91)	9.6	2.7		150
PBI	1.43	3.1 (0.4)	30	45 (5.7)	1.2	0.2		250
PBT	1.57	25 (3.5)	1.3	2690 (373)	9.6	10.3		350
PBO	1.57	24.6 (3.4)		2930 (406)	9.4	11.2		350
AB PBO	1.44	24.6 (3.1)		2430 (309)	9.4	9.2		350
Spectra 900	0.97	30 (2.6)	3.5	1400 (120)	11.5	5.3	38	100
Spectra 1000	0.97	35 (3.0)	2.7	2000 (171)	13.4	7.6	28	100
Thornel P55 Med M	1.8	10.8 (1.7)		1940 (308)	4.1	7.4	4–8	500
Thornel P100 HM	1.96	10.8 (1.86)	0.38	3300 (517)	4.1	12.6	4–8	600
Celion 3000 HS	1.8	25 (4.0)	1.8	1440 (230)	9.6	5.5		500
Boron	2.5	11.6 (2.55)	1.0	1800 (400)	4.4	6.9	33–140	2000
SiC	2.8	16 (4.0)	0.6	1700 (420)	6.1	6.5	10–12	1300
Alumina	3.25	6.3 (1.8)	1.2	730 (210)	2.4	2.8	17	1200
Nextel	2.5	7.8 (1.72)	2	690 (152)	3.0	2.6	13	1200
E glass	2.55	11.6 (2.6)	3	320 (72)	4.4	1.2	5–25	350
S glass	2.48	21.9 (4.8)	5.3	390 (85)	8.4	1.5	5–15	300
Steel	7.8	11 (7.6)	4.8	220 (150)	4.2	0.8		500
Dacron	1.38	9.2 (1.1)	15	115 (14)	3.5	0.4	25	150
Nylon 66	1.14	9 (0.9)	19	50 (8)	3.4	0.2	25	150

(From "Fundamentals of Composite Manufacturing")

Property	Carbon	Kevlar	S-Glass	E-Glass
Tensile Strength Ksi - MPa	500 - 3445	473 - 3260	575 - 3970	330 - 2275
Tensile Modulus Msi - Gpa	34 - 228	19 - 128	12.75 - 88	10.25 - 71
Elongation to break (%)	1.7	2.5	5.3	4.3
Density lb/in³ - g/cm3	0.065 - 1.8	0.052 - 1.44	0.090 - 2.48	0.093 - 2.57
Fatigue Resistance	Excellent	Good	Excellent	Good
Impact Strength	Fair	Excellent	V. Good	Good
Compressive Strength	Excellent	Fair	V. Good	Good
Compressive Modulus	Excellent	Good	V. Good	Good
Flexural Strength	Excellent	Good	V. Good	Good
Flexural Modulus	Excellent	V. Good	V. Good	Good
Impact Strength	Fair	Excellent	V. Good	Good
Inter-laminar Shear Strength	Excellent	Fair	Excellent	Excellent

(from http://www.corecomposites.com/products/reinforcements.html)

Weave Types and Tables of Comparisons

For an ideal situation, the following data shows that the twill weave keeps a good balance between stability and drape, both of which are important for this application. If twill weave is not available, a plain weave should be used.

Table 5: Weave Type Comparison

Property	Plain	Twill	Satin	Basket	Leno	Mock leno
Good stability	****	***	**	**	*****	***
Good drape	**	****	*****	***	*	**
Low porosity	***	****	*****	**	*	***
Smoothness	**	***	*****	**	*	**
Balance	****	****	**	****	**	****
Symmetrical	*****	***	*	***	*	****
Low crimp	**	***	*****	**	**/*****	**

***** = excellent, **** = good, *** = acceptable, ** = poor, * = very poor

Composite Material Recommendations

Although Kevlar is the obvious choice when it comes to overall strength, carbon fiber should be strong enough to withstand the forces that the tie rods would experience with a fairly high factor of safety. This fiber choice is usually accompanied with a polymer matrix. This material choice will ultimately save money and still function under acceptable parameters.

For the weave type, ideally a twill weave should be used. This weave offers a balance between strength, stability and drape. A plain weave would also be acceptable, but a basket or leno weave should be avoided.

3-D Modeling

Three Dimensional modeling through the use of computer aided design (CAD) programs has been an important technology to the engineering profession. CAD programs allow an engineer to create a model of a part or an assemblage of parts in order to virtually represent a visual model of the part or assembly before actually creating it. This saves time and money on prototypes and testing, which can be very valuable to completing a project in a timely and cost effective fashion. Part interfaces can also be checked and tolerance gaps can be measured in order to ensure that the product will function properly. CAD software is a valuable tool for engineers everywhere.

Creo Parametric

Modified from http://www.ptc.com/cad/3d-cad/creo-parametric
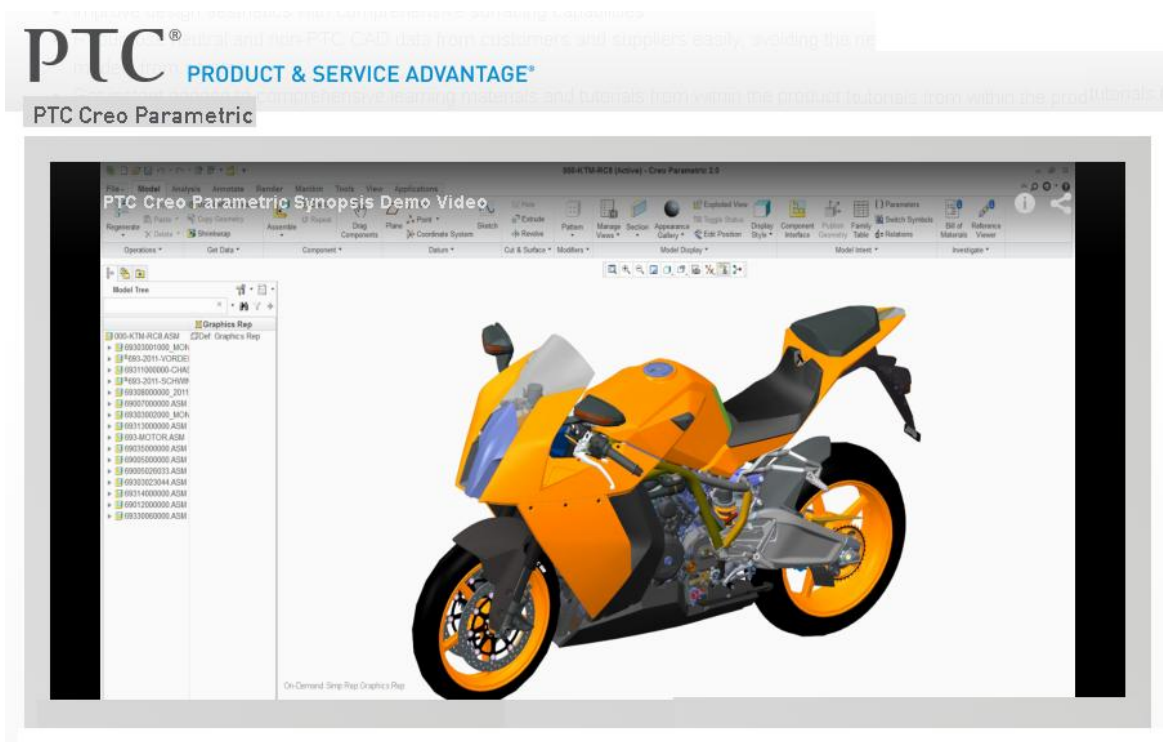
Creo Parametric is a type of three-dimensional modeling or CAD software that was created by PTC. (Note that it is not taught in the University of Akron curriculum like Solidworks is, but it is the software of choice for both the FSAE Electric team and Moen Incorporated, which is why I am most comfortable using this software.) Creo typically uses a three-axis coordinate system and corresponding planes as a workspace. The default planes in creo are named "Top", "Right", and "Front" planes. The z-axis corresponds to the intersection of the top and right planes, the x-axis corresponds to the intersection of the top and front planes, and the y-axis corresponds to the intersection of the right and front planes, as seen in the below figure. Three dimensional models are created by first sketching on a plane, then either using an extrude function or similar function. Extrudes can be used to either add or remove material. Creo also offers a wide range of possible model features to incorporate into a design. This program allows for three dimensional modeling to be made simple and intuitive.
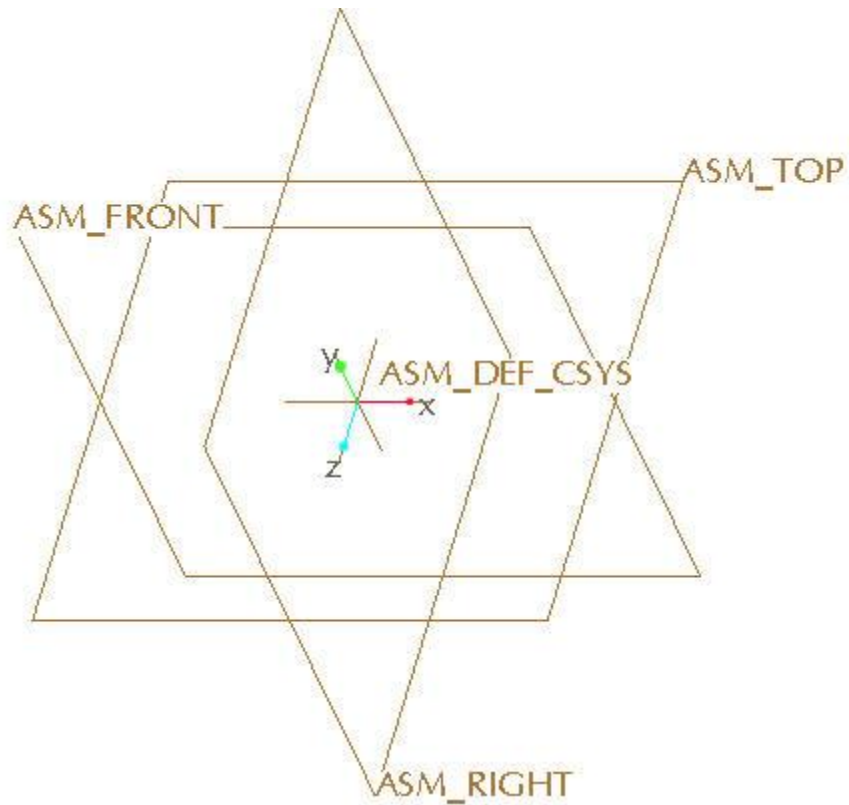
Creo allows for design both at the part level, and at the assembly level. This allows for complex full models and parts. Parts can be incorporated into an assembly through simple references and constraints. Using an assembly model can be very useful, especially when checking part interfaces. If a part is too big or too small, it can be easily checked through the CAD software. Along with assembly models, Creo has a function that allows the testing of the kinematics of a part through a function called Creo Simulate. This feature of the software allows the user to program moving parts into their model in order to view and analyze its movements. In addition to simulate, Creo also has built in FEA (Finite Element Analysis) software for analysis of a finished model or part. This feature allows the user to analyze the part or assembly under a variety of forces and with a variety of materials. Material properties of a specific material can

be downloaded and applied to a particular part, then tested under specific conditions to determine when failure will occur. More about FEA will be discussed in later sections.

Basic Modeling Techniques

Three dimensional design of a tie rod is a fairly simple. Because of this, simple modeling techniques were used. Sketching within CAD software is a term used to describe a two dimensional representation of the part on a particular plane. A sketch often represents one view of the part, as if looking directly at it from that side. This feature does not create any solid part, but is the building blocks to all solid parts in CAD software. From a sketch, a part can be extruded, which adds the third dimension to the part. If a sketch is in the front- top plane, an extrude can be made along the right plane direction. In addition to extrudes, revolves are commonly used to create a three dimensional solid in CAD. A revolve takes a sketch and revolves it around a specified axis. This is usually done in a full 360° revolution, but can also be reduced to create a revolve at any degree specification. Both revolves and extrudes can be used to add or remove material. These are the most common of the basic modeling techniques used for computer aided design.
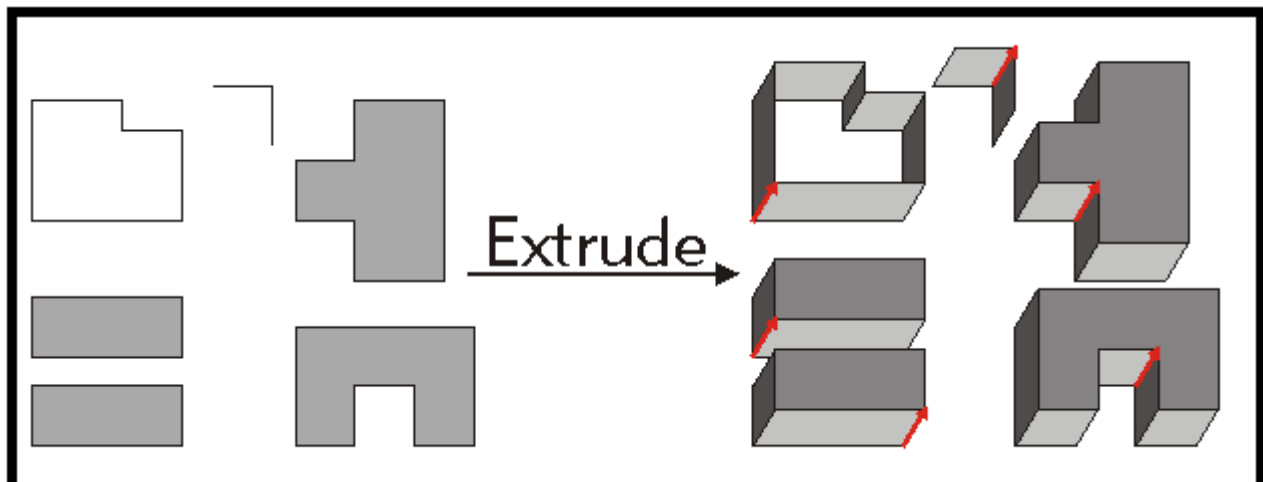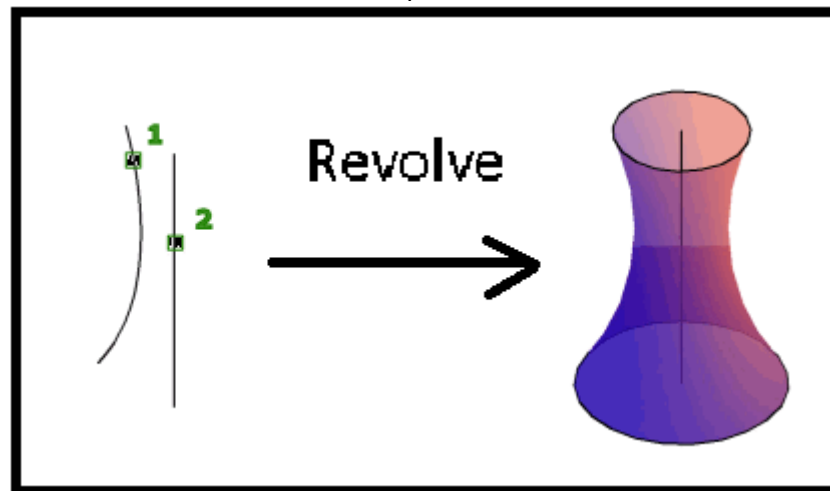
To begin the modeling of the tie rod, a sketch of the tie rod cross section was made, ensuring that the inner diameter, outer diameter, and wall thickness were as designed. This sketch was then extruded to the desired length. Another way to model this would be to define an axis at the junction of two of the basic planes. A box of the desired dimensions, length being the desired length of the rod and width being the desired wall thickness of the rod, can be drawn with a length corresponding to the inside diameter away from the axis. This sketch can then be revolved around the axis rather than extruded to create a solid. For inserts, the revolve function was used for the main structure of the insert. A helical sweep was used to create internal threads. This feature is much more complex than a revolve or extrude, and requires many more user inputs, such as thread profiles. A sketch of the thread profile is made and the depths, spacing and axis of revolution are specified. Modeling for camber links would be very similar to that of the tie rods, but the camber links were decided to be designed by another team member because it was decided that composites would not be used. Although the rules

prevented the use of composites for the CVT cover, the design of this in Creo would be slightly

different, but would use all of the same features such as extrudes and possibly revolves.

Full schematics of models created in Creo can be found in the appendix. This includes

both testing assemblies and parts and final design assemblies and parts. Drawings are also

provided for any parts that were machined.

FEA

FEA, which stands for Finite Element Analysis, is a method used to help determine when

a part or assembly may fail. Using FEA software, thousands of computations can be completed

in just minutes, creating a relatively decent model of internal stresses caused by specific forces

in the material designated. Using material designations, part meshes, and user defined

loadings, FEA software can be a very powerful tool in engineering design.

 For this project, Creo was used for modeling, but the FEA software in Creo Simulate is

not nearly as refined as the modeling software. Because of this, different software, ANSYS was

used, importing CAD part files into the new program.

Figure 19: ANSYS Program

Models and Placement of Loading

To begin, ANSYS Workbench was opened. The type of analysis was specified as "Static Structural." When analysis type is specified, the following box appears, which is used for setting up the analysis.
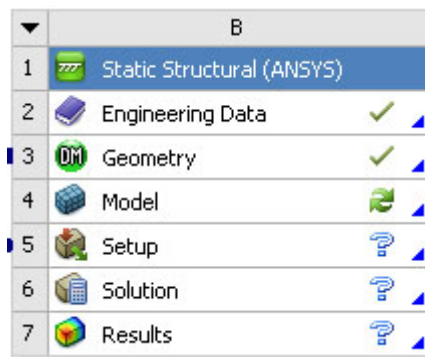
Within this box, there are several things that need to be assigned or defined. By double-clicking on engineering data, the material designation can be changed. This also allows the user to define material properties such as density and tensile strength. Under the geometry tab, the user defines the geometry which is to be analyzed. Model allows a user to check the imported model or create a new model from scratch. The set up tab has several things that must be defined. First, the mesh must be defined, which defines the size, shape, and resolution of the individual material elements which will be analyzed. This tab is also where constraints and forces are defined. The solution tab allows the user to specify what type of information is given and results are shown.

For the test assembly, materials were defined and CAD models from Creo Parametric were exported as ".igs" files into ANSYS so that the FEA program was able interpret the data, as

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seen in the below figure. The mesh was generated, changing the resolution from coarse to fine, also seen in the below figure. A fixed constraint was added on one end of the model and a tensile force was added to the other end. This will simulate the pulling of the assembly, like what would be done by a tensile test. Results were viewed and can be found in the FEA Results section.

Figure 21: Creo Assembly Model imported to ANSYS
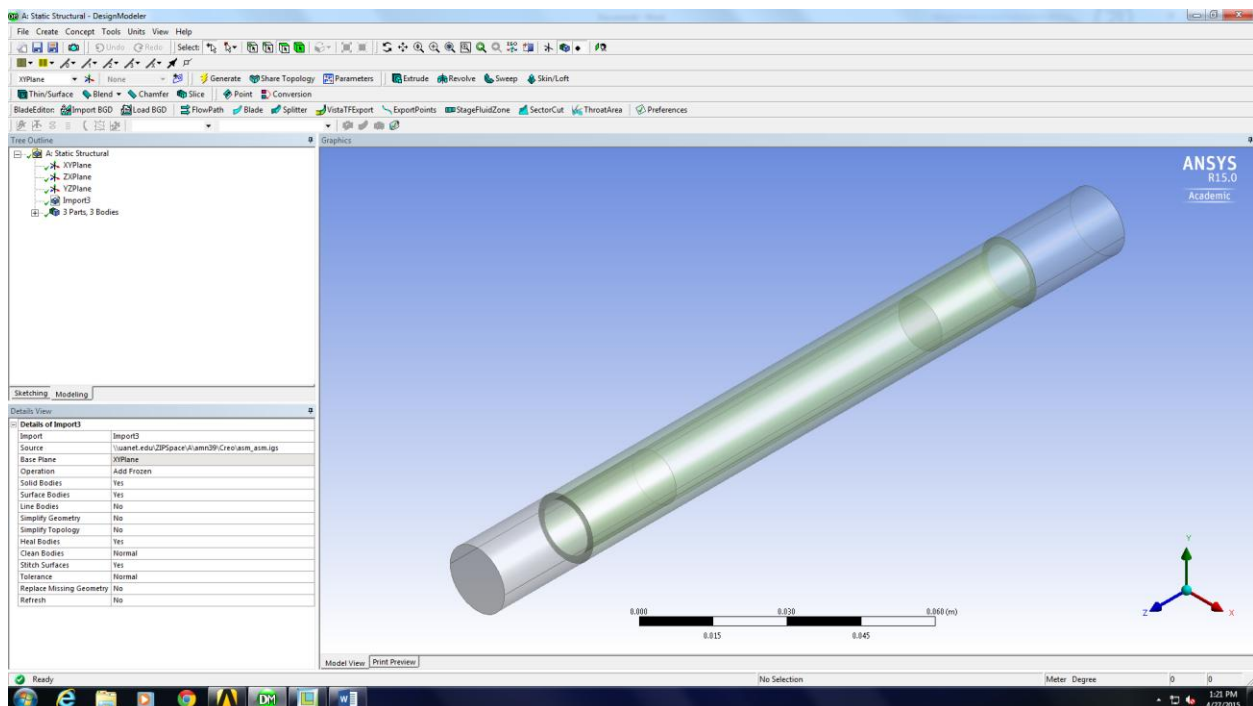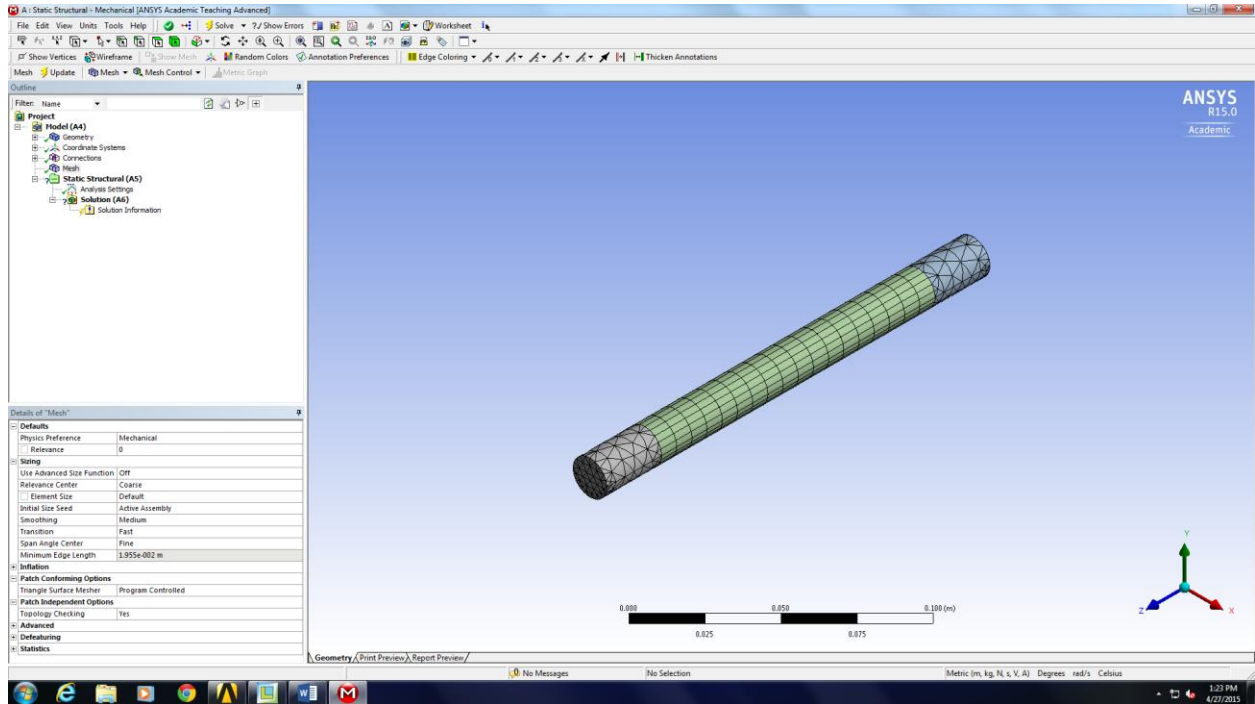
FEA Results

The results from the FEA program were somewhat surprising. It appears that the highest stresses are seen right at the bottom of the location where the inserts are fixed to the tube, assuming that the epoxy bond holds. This could be due to a stress concentration or the way the forces were applied to the model. The below picture illustrates the forces, with red being higher forces and blue being lower forces. This model is somewhat limited, due to the fact that the adhesive material to hold the inserts to the tube is not present in the model and analysis. Please refer to the appendix for the full mechanical report from ANSYS.

Figure 23: FEA Results
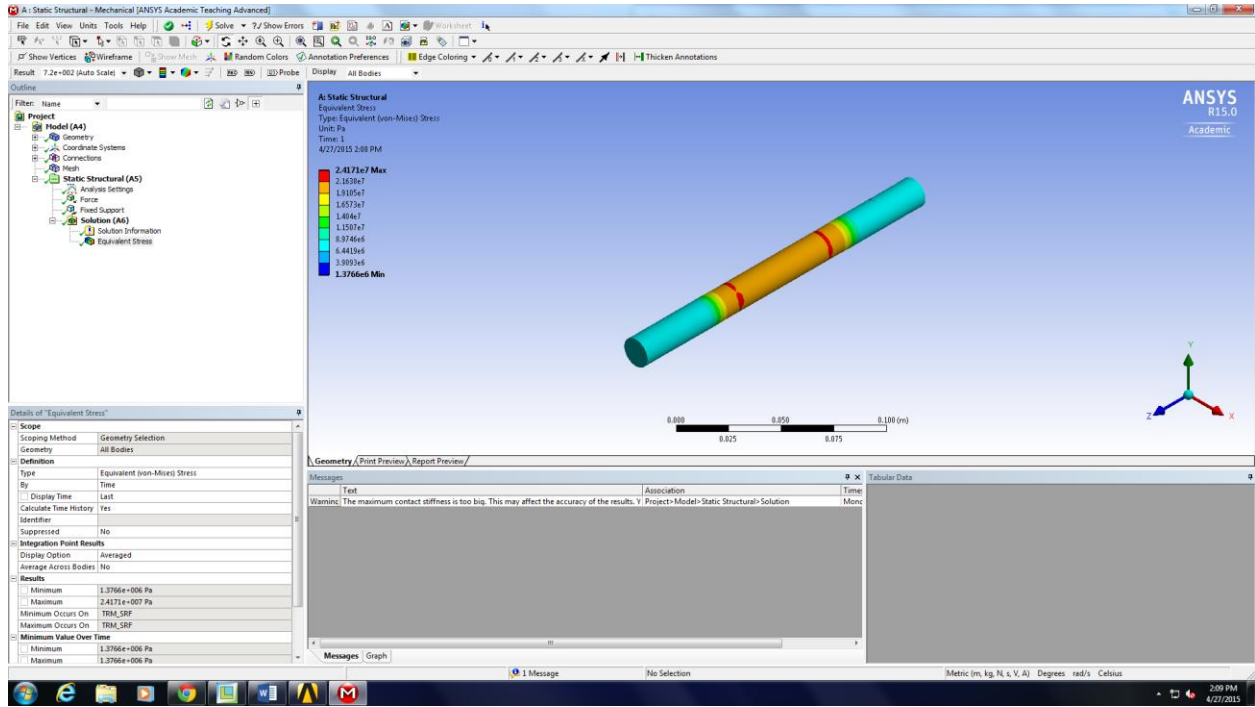
Adhesion Testing

Because the most common failure in composite tie rod design appeared to be in the adhesive bond, it was determined that the design of the composite tie rod should focus on creating a strong bond between the aluminum inserts and the carbon fiber rod. If the bond between the aluminum insert and the tube is not strong enough to support the loads applied to it, the strength of the composite material does not matter. Epoxy type and types of surface treatments, including sanding and aluminum etching will be analyzed for their effect on adhesion strength. Ideally, the carbon fiber tube will yield before the bond between it and its inserts.

When designing for adhesion, a few things should be considered. First, the differences in thermal expansion of both the insert material and carbon fiber materials should be considered, as well as the thermal expansion in the bonding element. Parts may not function the same way after exposed to extreme high temperatures. Another consideration should be differences in deformation. Metals, for example, will have plastic deformation prior to failure. Composite materials will not experience deformation and will rather fail all at once. This must be considered in the case that the assembly would fail.

Research into adhesion interface yielded that a tapered interface will generally be much more effective than a straight interface. A straight interface causes high stresses when a tensile load is applied. To minimize stresses, a tapered insert with variable thickness will produce a better adhesive surface, as illustrated below. Also below, an example of good and bad practices for inserts adhesion design is shown. This illustrates that a straight bond in the case of inserts

can be applicable due to the fact that there is 360° of contact with the adhesive material on

both surfaces. For simplicity, the decision was made to create inserts for testing that were

straight.

(From "Composite Materials Design and Applications" by Daniel Gay)
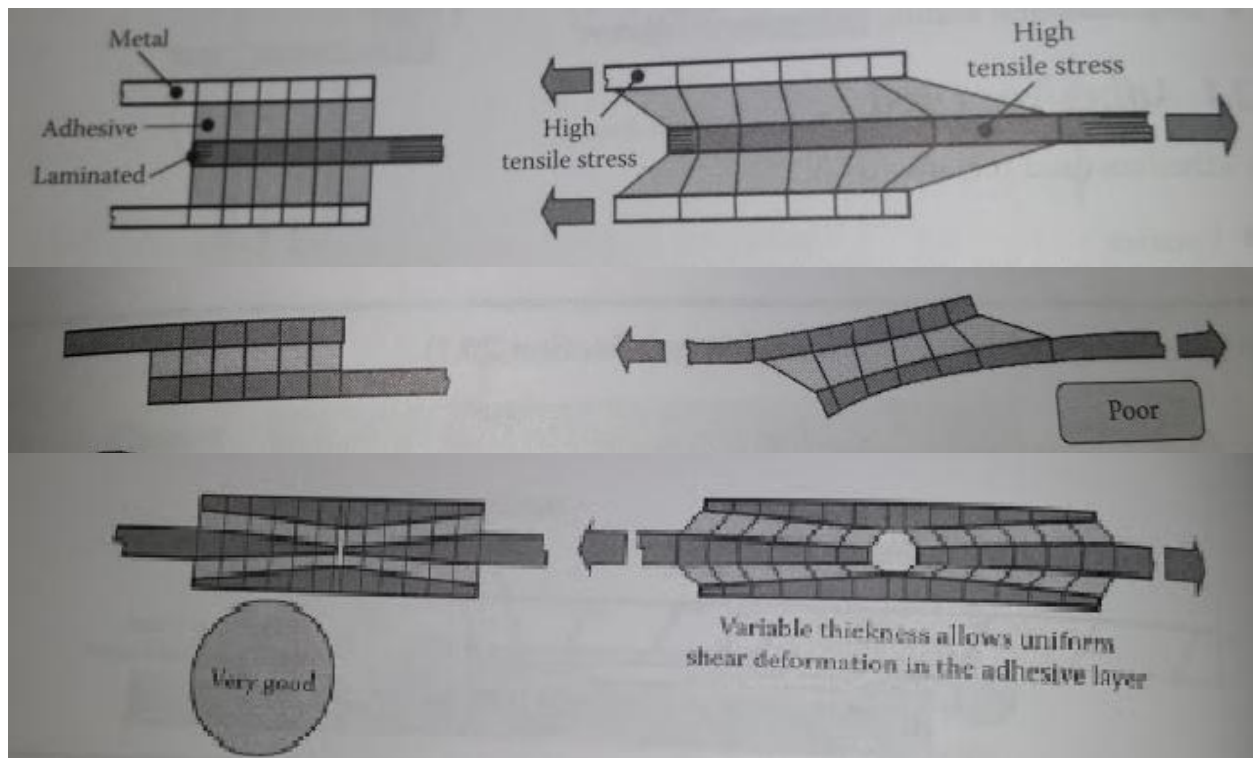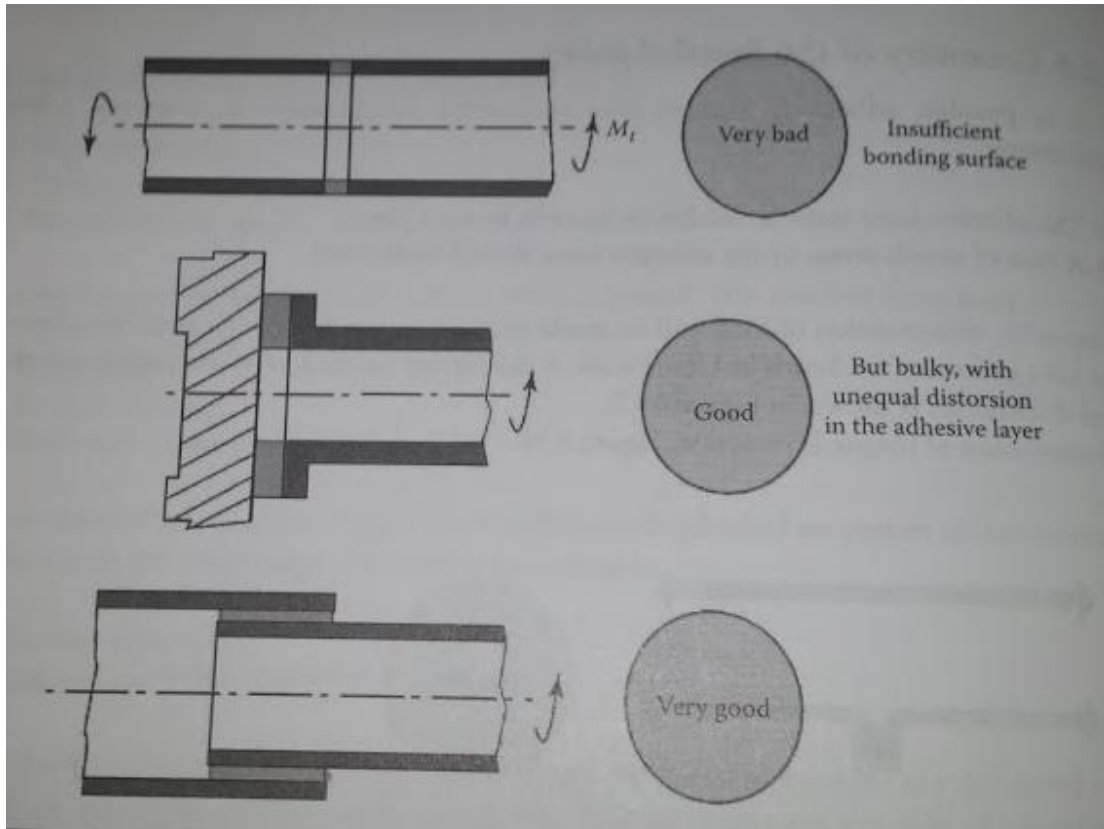
(From "Composite Materials Design and Applications" by Daniel Gay)

Surface Treatments

Surface treatment of both the carbon fiber and inserts is very important for proper

adhesion surfaces. With smooth surfaces on both components, the bonding material has less

surface area to contact and therefore less adhesion. If the surfaces are treated prior to bonding,

a stronger bond will be formed. From research, the most common form of failure in composite

tie rods is loss of adhesion between the insert and the composite tube.

The inserts were tested with no surface treatment, and with sanding as a surface

treatment. Additional surface preparation, aluminum etching, will be explored if aluminum is

chosen as the material for the insert and if tensile testing produces a failure of the adhesive alone. Ideally, the composite tubes will fail before the bond of the tube and the insert. The inserts are not expected to fail before the composite tube.
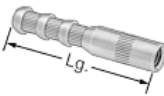
Inserts

For the inserts, many options were considered. The first option considered was to machine inserts using the machine shop in the basement of the Auburn Science and Engineering building. This would require getting machine shop safety and machine training, learning how to use and set up the lathe, and purchasing aluminum rods to use on the machine. This option would also allow for the most customizable insert and would be ideal for testing and design.

Another consideration was to purchase threaded inserts. When searching for threaded inserts on McMaster Carr, only two possible options were found. These options were considered because of their size, length and strength. Both options can be seen in the below figures.

Figure 26: McMaster Carr Option 1

Adhesive-Grip Internally Threaded Anchors for Concrete

Anchors are internally threaded for high pull-out strength in shallow concrete holes as well as where high vibration is present. Fill a clean, drilled hole half full with epoxy adhesive, then insert the anchor until it's flush with the surface. All have Class 2B thread fit. Ultimate pull-out strength is based on tests using epoxy adhesive in 3,000 psi concrete.
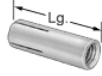
Type 316 stainless steel is more corrosion resistant than zinc-plated steel and may be mildly magnetic.

Warning! Allowable pull-out strength is 25% of ultimate values or less, as required by building authorities.

For Screw Size	Lg.	Drill Size	Drilled Hole Dp.	Ultimate Pull-Out Strength, lbs.	Thread Dp.	Type 316 Stainless Steel	Each	Zinc-Plated Steel	Each
1/4"-20	1 5/8"	5/16"	1 3/4"	2,900	1/2"	93980A530	$5.95	93980A110	$1.38
5/16"-18	2 3/8"	7/16"	2 3/4"	7,500	3/4"	93980A550	9.47	93980A130	1.92
3/8"-16	2 3/4"	1/2"	3 1/4"	9,300	1"	93980A570	12.11	93980A150	2.43
1/2"-13	3 3/4"	5/8"	4 1/8"	13,100	1"	93980A590	18.42	93980A170	4.08
5/8"-11	5 3/4"	7/8"	6 1/4"	26,000	1 1/2"	93980A630	53.85	93980A190	16.97
3/4"-10	6 1/2"	1"	7 1/2"	36,000	1 1/2"	93980A650	71.79	93980A210	20.38
1"-8	8 1/2"	1 1/2"	9 1/2"	51,000	2"	93980A670	116.67	93980A230	58.17

For both of these options, the application was intended for concrete and both potential

insert options are made of steel rather than aluminum. The first option was considered because

of its tapered end. The idea was that the bonding material would fill the gaps and create a

stronger bond between the carbon fiber tube and the insert. The areas where the tapers were

would have a large amount of adhesive, causing a thicker, more difficult bond to break. The

second option was considered because the bottom of the insert allowed wedging the piece into

the tube. In order to get a better idea of how these products might be applied to the project at

hand, two pieces of each were ordered.

Although they were the right size and shape, it was determined that these pieces were

ultimately not the best option for this application for several reasons. First, they are both made

of steel. This increases the weight of the assembly as a whole which is not desirable in this case.

For the first option, the weight was the only reason for the decision, but for the second, other

cases were considered. As stated previously, the second potential insert would require

wedging, which was determined to be a potential hazard to the carbon tube. The material, to

accommodate the insert, would be forced outward, potentially causing extra stress concentrations in a crucial area of the tube.

The ultimate decision was made to machine aluminum inserts, despite the extra work involved. This is due to the fact that they would be customized and lighter weight than the other options. Aluminum rods were purchased and the proper training was acquired in order to use the machine shop.

Manufacturing of Testing Inserts

In order to test the adhesion strength of the carbon fiber and aluminum inserts, a set of testing inserts were manufactured in order to use the testing equipment available without damaging the actual inserts. A lathe in the machine shop was used to machine the inserts.

Figure 28: Lathe used to Machine Inserts

Aluminum with a diameter of 0.75 inch was used as the material. Sections were cut approximately 4 inches in length using the cut off saw in the machine shop. These smaller pieces of aluminum were placed in the lathe and tightened into place. The cutting tool, shown below, was placed and centered.

Figure 29: Cutting Tool for the Lathe
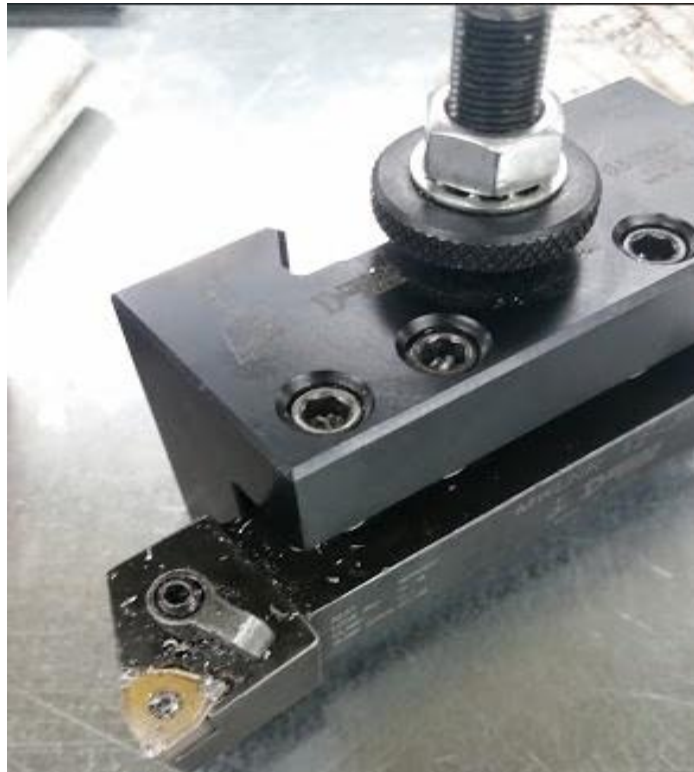
After the cutting tool and the aluminum were both tightly secured into place, the machine was set to the appropriate speed for aluminum, the stop was placed so that the machine could only remove material to a length of 2 inches, and the machine was turned on. The end of the aluminum was first cleaned up to have a better aesthetic appearance. After that, material was removed in small amounts at a time. The auto feed was used to ensure that cuts made were even and clean.

The diameter of the aluminum rod was reduced from 0.75 inches to 0.615 inches. After this, the machine was stopped and cleaned up and the position of the stop was moved from 2 inches to 1 inch. The next part of the insert was machined, further reducing the diameter to 0.490 inches. A parting tool was used to remove the insert from the rest of the aluminum rod.

Figure 31: Aluminum Inserts Before and After Parting

Assembly of the Test Piece

The test piece was assembled to ensure that the parts fit in the tube and that there were no unwanted gaps. Two inserts were placed within one of the carbon fiber tubes, one on each end. Both fit with plenty of clearance, allowing sufficient space for a bonding agent.

Testing Equipment

For tensile testing, the Instron machine in the materials lab in the basement of ASEC is used. This particular machine, which is model 5582 Instron, was used with 20,000 pound load cells. The standard grips with round stock plates were used to grip the test piece. The computer ran Bluehill 2 as the data acquisition program.

Testing Procedures

The adhesion strength between the aluminum inserts and the carbon fiber tube were to be tested. This decision was made due to the fact that the top form of failure for other teams that have attempted to use carbon fiber as tie rods was a failure of the bond between the inserts and the carbon fiber tube. Ideally, the adhesive bond would not break. Rather, the

carbon fiber tube would rupture or delaminate. The following tests were conducted in order to test adhesion strength and to determine what adhesives would work best for this application.

Testing Round One

To create a baseline for the testing, a high strength carbon fiber epoxy, Fletch-Tite, was used for testing. This epoxy is designed for carbon fiber arrow shafts with aluminum inserts, so the intended materials for the application are essentially the same. The inserts, as stated previously, will be custom made from aluminum using the machine shop in the basement of the Auburn Science and Engineering building. The tubes are roll wrapped carbon fiber ferrules with a plain weave, which were purchased online and selected for their size and cost. The specifications of the tubes and schematics for the inserts as well as the tubes can be found in the appendix.

The baseline test was conducted with no surface treatment. Epoxy was applied to the tube generously and the inserts were inserted into the carbon fiber tube. Because of the pressure created by the test inserts, closing off both ends by gluing both inserts at one time causes one side or the other to slowly work its way out, so one insert at a time must be placed. The insert was clamped to the tube, applying pressure so the bond will be as strong as possible. This particular epoxy requires two days of cure time at room temperatures, so one part of the assembly was assembled with two days to cure, and the other side was assembled with two days to cure for a total of five days, with one day time in between for preparation.

After the sample was prepared, the inserts were pulled on to test adhesion strength. Results were collected and data was recorded (can be found in results and discussion section). This process was repeated an additional two times to verify results.

Testing Round Two

For this round of testing, the same procedures were followed for round one, except that both surfaces were treated. Both the inserts and the carbon fiber tube were cleaned of any adhesive residue using acetone. This was done in order to remove any source of error from old adhesive in the tube. For the inserts, high grit sand paper was used to create a rough surface where the adhesive will be bonding. For the carbon fiber tube, the inside of the tube where the two parts will interface was sanded, again creating a rough surface for the adhesive to grab on to. The same adhesive and process for assembly was used. Testing was conducted and data was collected.

Testing Round Three

Because the first type of adhesive did not hold, additional research was conducted to see what other teams have tried. The decision to switch to the adhesive called Gorilla Glue was made. This glue, unlike the previous adhesive, is activated by and cured by moisture.

To prepare the assembly, the surfaces were once again cleaned with acetone to avoid cross contamination of the adhesives. The surfaces were re-sanded gently to ensure that the surfaces have sufficient roughness for bonding. Water was filled into a spray mister and used to

wet both the aluminum insert surface and the surface of the carbon fiber tube. The new adhesive was applied to the inside of the tube and one insert was placed in the tube.

As it is cured, this new adhesive type expands into a foam like substance which helps to bond the two parts. From the other end of the tube, the expansion of the foam was watched to ensure that the foam did not expand beyond the point which the other insert needed to be inserted. The cure time for this glue is two hours, after which the second insert was placed into the tube in the same way.

For this testing, a special machine was used because the force to pull the tube exceeded the force that the hand held measuring device could read. The machine used is located in the basement of Auburn Science and Engineering building and is called and Instron. Details and background information about this machine can be found in the testing equipment section. Permission had to be obtained to use this particular machine. Cliff Bailey helped to perform the tests.

After initially setting up the test, it was realized that the inserts were too large to fit in the jaws of the Instron machine. The diameter was quickly reduced from 0.615 inches to 0.500 inches, with a length of 0.75 inches to accommodate for the maximum amount of grip without compromising the integrity of the carbon fiber tube. A new model and a photo of the new testing insert are shown below.
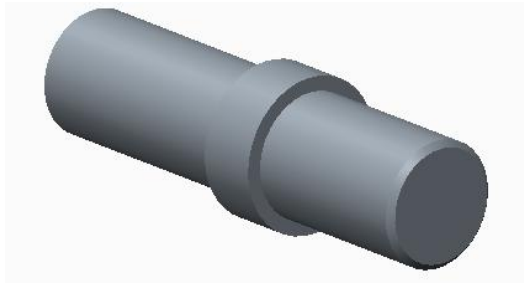
After the inserts were modified, the load cells were loaded into the Instron and the proper jaws attached using the set pin. The program, Bluehill 2 which is used in combination with the Instron machine, was launched. A program from the University of Akron Formula team was altered to accommodate the testing specifications for this particular test. Data was set to record one data point every second and the feed rate was set to 150 pounds per minute. The test sample was clamped into the machine and tightened into place. The machine applied a tensile force, pulling on the inserts until rupture, either in the adhesive bond, the carbon fiber tube, or the aluminum inserts occurred. Results were collected and data saved.

Figure 34: Procedures for Instron Testing- Set up and Bluehill Program
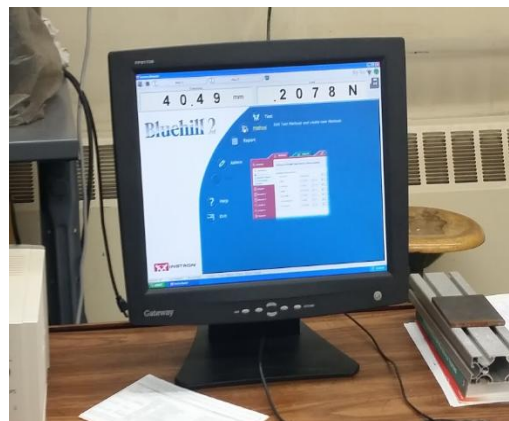
Figure 35:Procedures for Instron Testing- Grip Marks on Insert from Machine and Final Test Piece
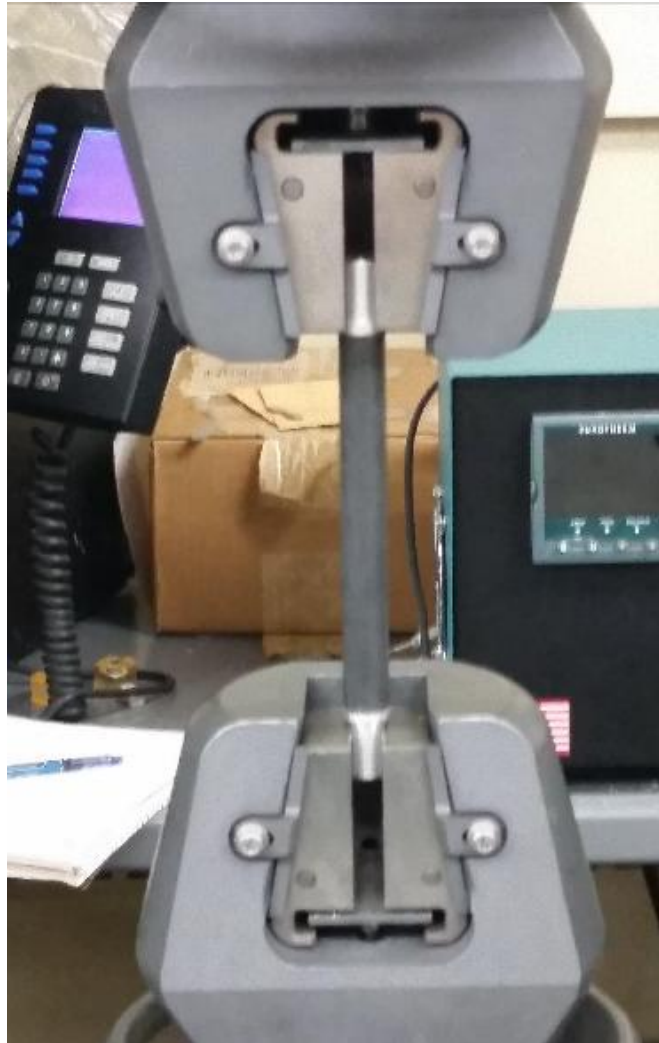
Results

For testing round one, the inserts were pulled on in order to test the bond. The inserts popped right out, with a force estimated as less than 10 lbs. The same test was conducted an additional two times in order to verify that the bond did not hold. Both unfortunately yielded similar results. Although it was expected that the bond would not be very strong, this was significantly less force than expected. These tests were not measured due to the fact that it was apparent that the bond would not hold. Techniques for round two were altered.

For round two of testing, the aluminum inserts and carbon fiber tubes were sanded in order to increase the adhesion strength. Again, this test yielded disappointing results for all three test pieces. The bond was much stronger, but still only yielded an average pull force of 18.5 lbs to remove the insert, which is well below what would be needed.

For the third round, the epoxy choice was switched up. With this new bond, the test piece survived the hand test. It was decided to use this method of bonding in the Instron to conduct a formal test. The above procedures were followed, with a few minor hiccups. The results from testing can be seen below.
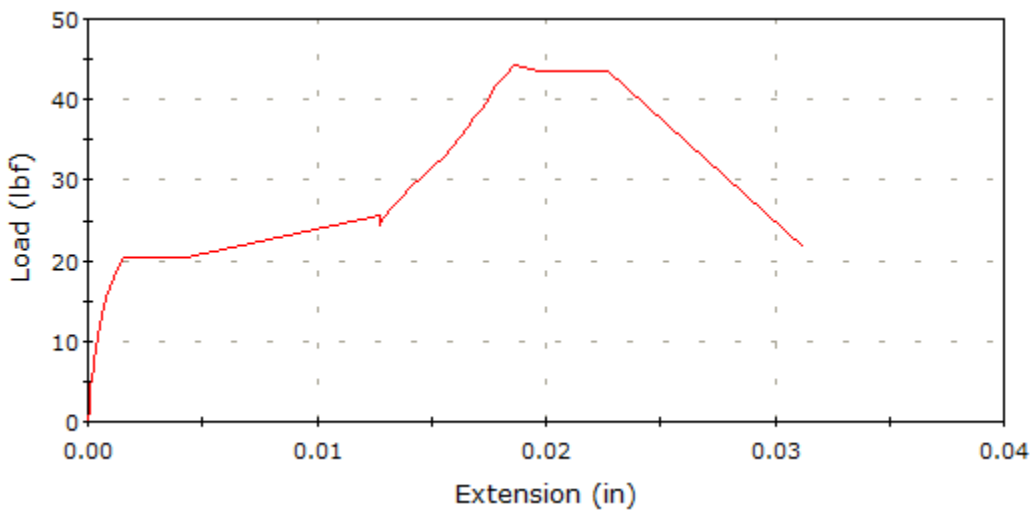
This epoxy only allowed for 45 pounds of tensile force. This again is much less than would be needed in an application. For future testing, the bond will need to be much stronger. The bond strength of the bond material was rated to 150 lbs minimum. The gap in actual vs specified adhesion strength could be due to any number of reasons. For one, the amount of gap between the inserts and the tube wall may not have been sufficient to create enough of a bond. Another

possibility could be the amount of surface treatment for both pieces. In the next section a few recommendations will be made. Full results from the Instron can be found in the appendix.

Final Design Recommendations

For the materials of this particular design, it is recommended that carbon fiber is used, due to the fact that the composite material itself was not the source of failure. Additionally, the aluminum inserts were not the source of failure and can thus be used as well. This is the most cost effective solution under the current conditions. Additional testing should be conducted with additional bonding agents to determine if a better solution is available.

Although a time restriction did not allow for additional testing of multiple adhesion types and designs, a further recommendation would be to create a pin through the carbon fiber rod and insert which would provide additional support for the bond in tension and in compression. This could prevent the issue found with bond strength. A Creo model of the design can be seen below for future reference and testing. The tube is partially transparent to illustrate the inside of the proposed testing piece. Another option would be to modify the part of the insert which is inserted into the tube to have multiple tapers, similar in shape and concept to a porcupine quill. This might allow for additional adhesive to build up in those areas creating a stronger bond. An example of an insert using this concept is also shown below.

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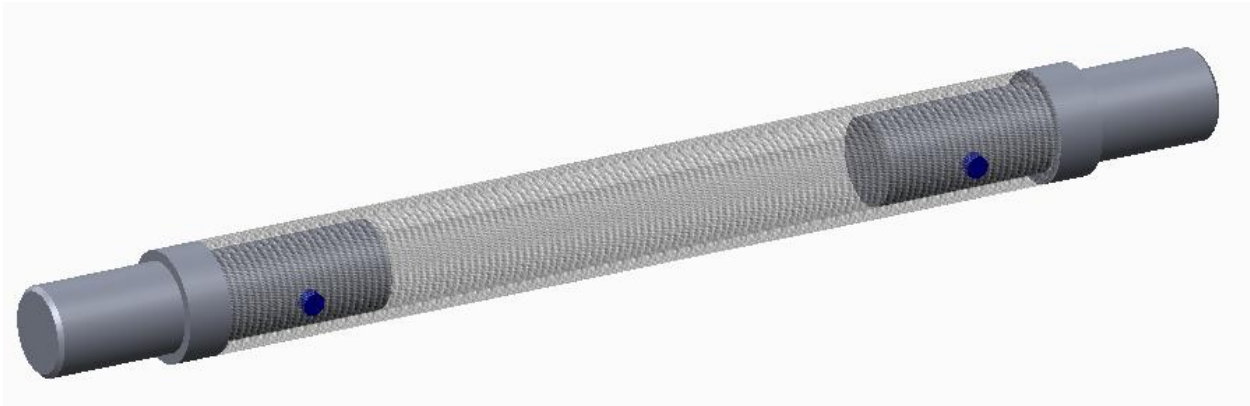
Part III: Relationships to Undergraduate Curriculum

At the University of Akron, the undergraduate curriculum is designed to prepare students to enter the workforce after graduation. This is done through requiring several classes for students to take. As a capstone report, it is important to reflect on how the undergraduate curriculum has prepared me as a student for this project.

First of all, classes such as Calculus and Physics, even Statics, which all engineering students must take, provide an introduction into the mindset and thinking of an engineer. They also are the building blocks to all engineering classes offered and are therefore very important and should not be thought of as simply general education classes, but rather stepping stones in the process of learning. These classes are an important foundation to the engineering curriculum.

One of the first classes that engineering students at the University of Akron are exposed to is called "Tools for Mechanical Engineering". This course serves as an introduction to engineering concepts and ideas, as well as exposure to basic computer programs that engineers use on a regular basis. In this class, the main benefit for this project came from the introduction to the Solidworks modeling software. Students are taught basic cad modeling skills which was incredibly helpful in this project, specifically for the visualization of parts before manufacture. With this knowledge, students are able to apply modeling software to their projects, not only to use 3D models, but also for 2D drawings which were dimensioned using skills taught in the

tools class as well. This class serves as an introduction, but also as a foundation for further learning throughout the engineering curriculum.

Another one of the first engineering classes that we as students are exposed to is dynamics. This class is the foundation for many other classes and thus very important. Even for this project, basic vehicle dynamics are used to estimate tie rod forces. Similarly related to dynamics is the elective course, Vehicle Dynamics. This course builds from a basic understanding of dynamics and applies it specifically to vehicles. These courses help to define the foundations of calculations for this particular project.

Analysis of mechanical components and design of mechanical components were two classes that go hand in hand with the skills gained for this project. With these two classes, the basics of material stresses and failure is considered, along with how to design to avoid failure. The mathematics behind the FEA program used to analyze stresses was also introduced in these courses. These courses create the foundation of thoughtful engineering design.

COD, which stands for Concepts of Design, is another important class which mechanical engineering students take as part of the required curriculum. This course allows students to begin to think as a designer. Through a handful of design tasks, students are exposed to working in teams, hands-on assignments, as well as basic machine and safety training.

Mechanical Engineering Measurements Lab and Mechanical Engineering Lab both serve as helpful courses, teaching students how to prepare and conduct laboratory testing. With both of these classes, students are given the opportunity to run tests, collect data, and draw conclusions about the data collected. These classes also expose students to a variety of testing

equipment which is available for their use.

Other Engineering classes, although not directly related to this particular project, still provide valuable insight into the field of engineering and help prepare students for outside work. These classes include classes such as Thermodynamics, Fluids, Mechanical Vibrations, along with many others. Overall, the University of Akron curriculum does an excellent job preparing students to design, manufacture, and conduct testing of their own.

Finally, it is important to mention that co-op experience has also had a tremendous impact on the skills and abilities needed, both for this project and for entering the work force. At a co-op, students are exposed to what the real world of engineering is like. They conduct real tests and design real products, often with guidance. These rotations allow for students to widen their experiences and learning beyond the classroom. Without co-op experience, many students would not have a full understanding of how engineering applies to the real world. This experience is crucial to having a head start in a career.

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Appendix

Project Timeline

Project Schedule	(Updated Monthly)					
October	**November**	**December**	**January**	**February**	**March**	**April**
1 Select project	Initial SAE Message Boards Research	Read Strong's Book	Material Choices Finalized	Purchase Parts	Initial Testing	Finish Testing
2 Write Proposal and Acquire Signatures	Look for Books at ASEC Library	Read Gay's Book	Design in CAD	Machine and safety training	Begin Outline for Final Report	Write Final Report
3 Create Project Timeline	Internet Research	Begin epoxy research	ANSYS analysis	Machine Inserts		
4	Seak Funding/Sponsorship		Design testing procedures	Research Surface Prep		
5	Create Budget					

Baja ZB15 Information

Figure 39: Team Picture

Figure 40: University of Akron ZB15

Table 7: UA Baja 2015 Steering Specifications

University of Akron 2015 Baja Steering Specifications	
Ackerman %	0% (Parallel)
Rack Ratio	3.5:1 (deg/deg)
Max Steer Angle (L & R)	40°
Max Bump Steer Toe Angle	0.27°
Lock to Lock Rotation	280°
Total Rack Travel	4"
Static Tie Rod Angle to Ground	2°
Steering Arm Length	3.125"
Caster Angle	11°
Scrub Radius	0.85"
Mechanical Trail	0.51"
Steering Wheel Diameter	9"
Front Tires	GBC XC-Master 22x7.00-10
Total System Weight	8.39 lbs

Table 8: Steel Tie Rod Calculations (From Baja Design Report)

Tie Rod		
F	75.61	lb
E	29700000	psi
L	14.27	in
Density	0.284	lb/in^3

F crit = Maximum axial load when buckling occurs

Ꮎ comp = compression stress due to axial force

Diameter (in)	Wall (in)	Area (in^2)	Weight (lb)	I (in^4)	F crit (lb)	Ꮎ comp (psi)
0.75	0.058	0.066	0.937	0.0043	6145	1152
0.75	0.035	0.040	0.574	0.0027	3884	1878
0.625	0.065	0.060	0.863	0.0027	3827	1250
0.625	0.058	0.054	0.774	0.0024	3474	1393

Table 9: Reference Drill and Tap Chart

Tap size	NF/UNF	Threads per inch	Basic major dia (inches)	Basic effective dia (inches)	Basic minor dia of ext. threads (inches)	Basic minor dia of int. threads (inches)	Drill size (inches, wire & letter)	Drill size (mm)
1-64	UNC	64	.0730	.0629	.0538	.0561	#54	1.55mm
2-56	UNC	56	.0860	.0744	.0641	.0667	#50	1.85mm
3-48	UNC	48					#45	2.1mm
4-40	UNC	40	.1120	.0958	.0813	.0849	#43	2.35mm
5-40	UNC	40	.1250	.1088	.0943	.0979	#38	2.65mm
6-32	UNC	32	.1360	.1177	.0997	.1042	#36	2.85mm
8-32	UNC	32	.1640	.1437	.1257	.1302	#29	3.5mm
10-24	UNC	24	.1900	.1629	.1389	.1449	#25	3.9mm
12-24	UNC	24					#16	4.5mm
1/4- 20	UNC	20	.2500	.2175	.1887	.1959	#7	5.1mm
5/16-18	UNC	18	.3125	.2764	.2443	.2524	F	6.6mm
3/8- 16	UNC	16	.3750	.3344	.2983	.3073	5/16	8mm
7/16- 14	UNC	14	.4375	.3911	.3499	.3602	U	9.4mm
1/2- 13	UNC	13	.5000	.4500	.4056	.4167	27/64	10.8mm
9/16- 12	UNC	12	.5625	.5084	.4603	.4723	31/64	12.2mm
5/8- 11	UNC	11	.6250	.5660	.5135	.5266	17/32	13.5mm
3/4- 10	UNC	10	.7500	.6650	.6273	.6417	21/32	16.5mm
7/8- 9	UNC	9	.8750	.8028	.7387	.7547	49/64	19.5mm
1" - 8	UNC	8	1.0000	.9188	.8466	.8647	7/8	22.25mm
1.1/8 – 7	UNC	7	1.1250	1.0322	.9497	.9704	63/64	25mm
1.1/4 – 7	UNC	7	1.2500	1.1572	1.0747	1.0954	1.7/64	28mm
1.3/8 – 6	UNC	6	1.3750	1.2667	1.1705	1.1946	1.13/64	30.75mm
1.1/2 – 6	UNC	6	1.5000	1.3917	1.2955	1.3196	1.11/32	34mm
1.3/4 – 5	UNC	5	1.7500	1.6201	1.5046	1.5335	1.35/64	39.5mm
2" - 4.5	UNC	4.1/2	2.0000	1.8557	1.7274	1.7594	1.25/32	45.24mm

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Testing Materials and Models

INNER FERRULE TUBES

Now you can create tubes longer than 60"! Our new inner ferrule tubes are designed to splice our most popular small and medium tubes together to give you any length you desire. Each ferrule has been sanded to provide a .005-.006" bond gap which is ideal for many structural adhesives. For instance our .490" OD ferrule is sized to fit inside our .500" ID stock tube. Our ferrules save you the cost of buying a full length tube to connect two larger tubes. In the image below you will notice our ferrules look different from our other tubes. On the very last ply in the tube layup we add a prepreg fiberglass veil which offers a few benefits. One reason we added the fiberglass veil is to provide some shock absorption to the joint. Fiberglass isn't quite as stiff as carbon so it does this job very well. Another benefit in some applications is the ability for fiberglass to insulate a joint when bonding carbon to metal. If you cannot insulate the joint galvanic corrosion may become an issue. For a "how-to" guide on bonding tubes please see our cut and bond page.

Ferrule pricing includes First Class Mail Shipping

OD inches	ID inches	WALL inches	LENGTH inches	WEIGHT lbs / ft.	PRODUCT ID/DESCRIPTION	PRICE	BUY NOW
.490"	.375"	.058"	5"	.021	SM490FER \ Roll Wrapped Uni with Fiberglass Veil	$9.64	Add to Cart
.615"	.500"	.058"	5"	.028	SM615FER \ Roll Wrapped Uni with Fiberglass Veil	$10.15	Add to Cart

Figure 42: Testing Insert

Figure 43: Testing 3D Assembly

Figure 44: Drawing of Testing Insert (for Machining)
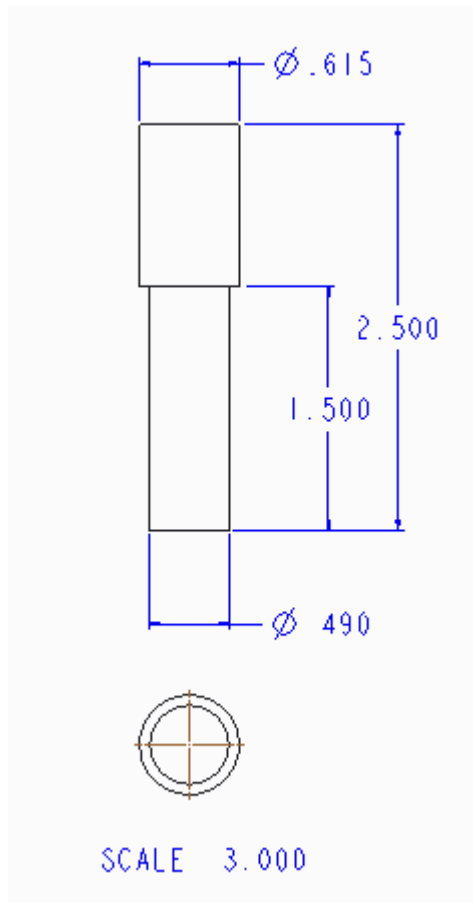
Figure 45: Modified Insert
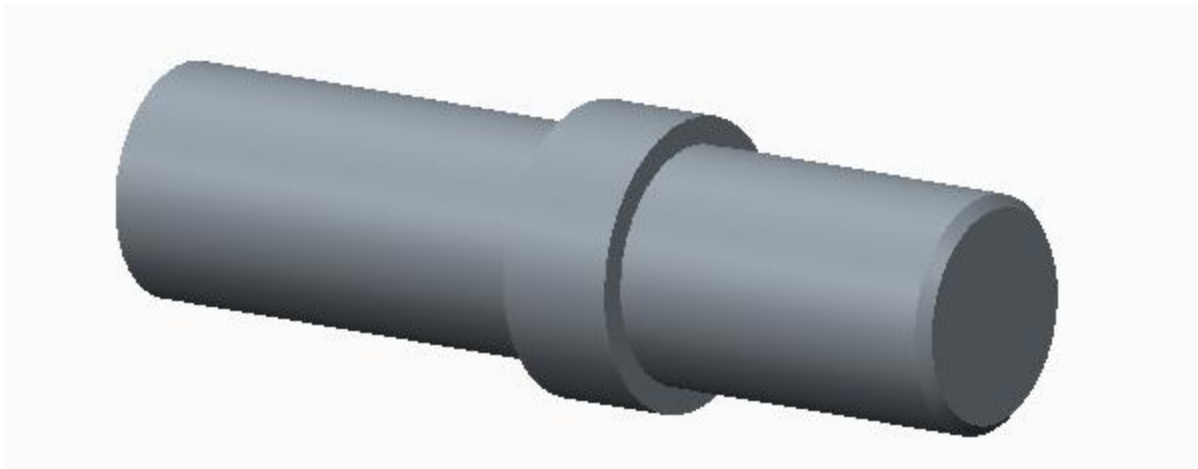
Figure 46: Pin (Optional Design Choice, Diameter=0.13 in)
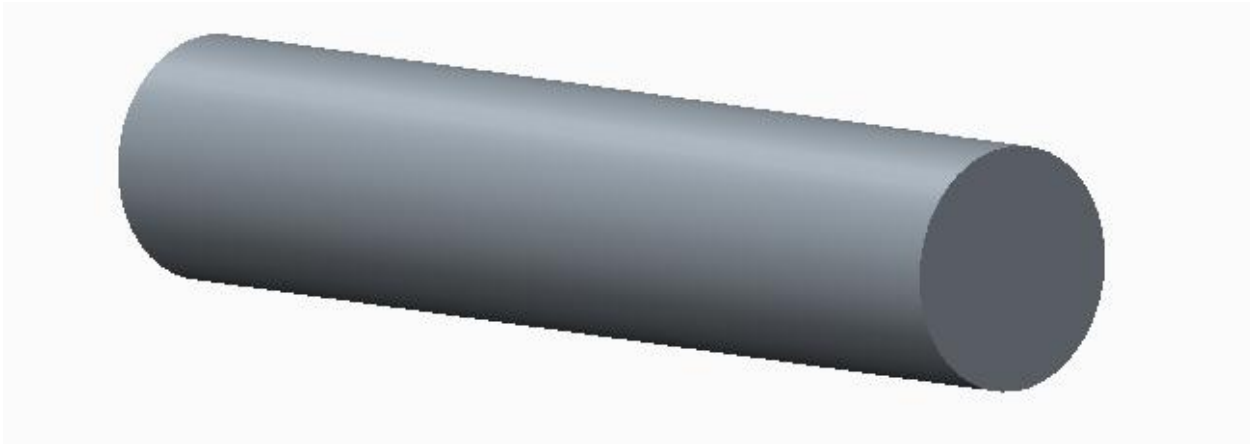
Figure 47: Modified Insert With Pin Option
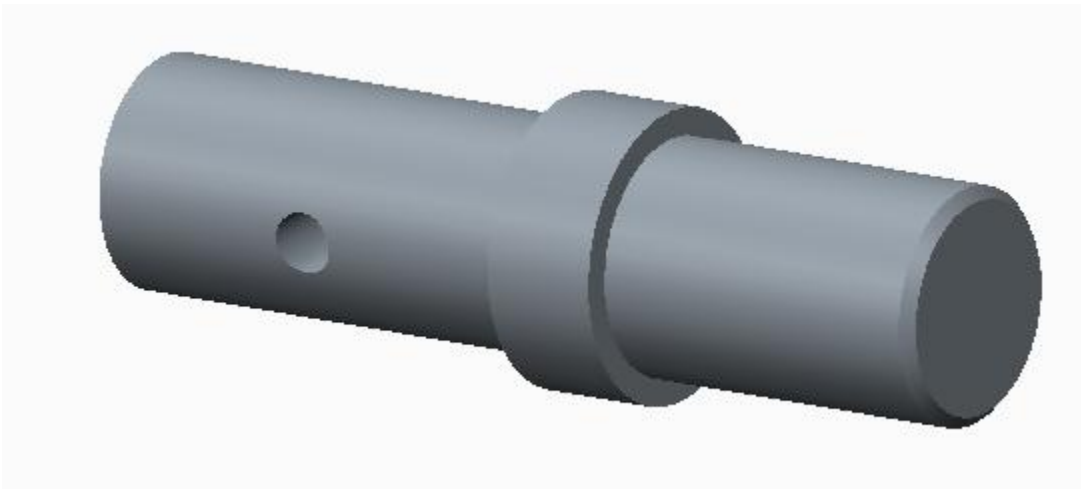
Figure 48: Modified Assembly with Pin
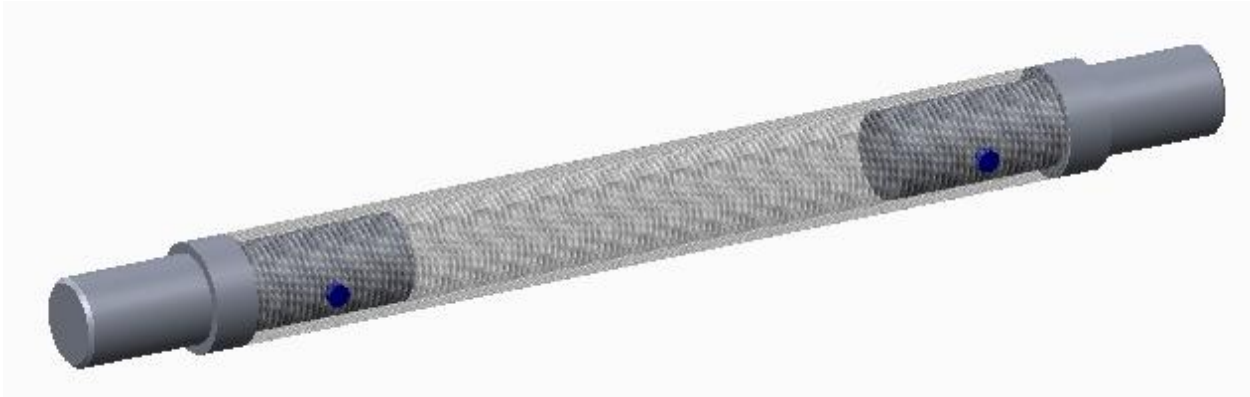
Testing Data and Charts

Tension Test of Aluminum Inserts with Carbon Fiber Tube

Test: Rate 1	150.00000 lbf/min

Specimen 1 to 1
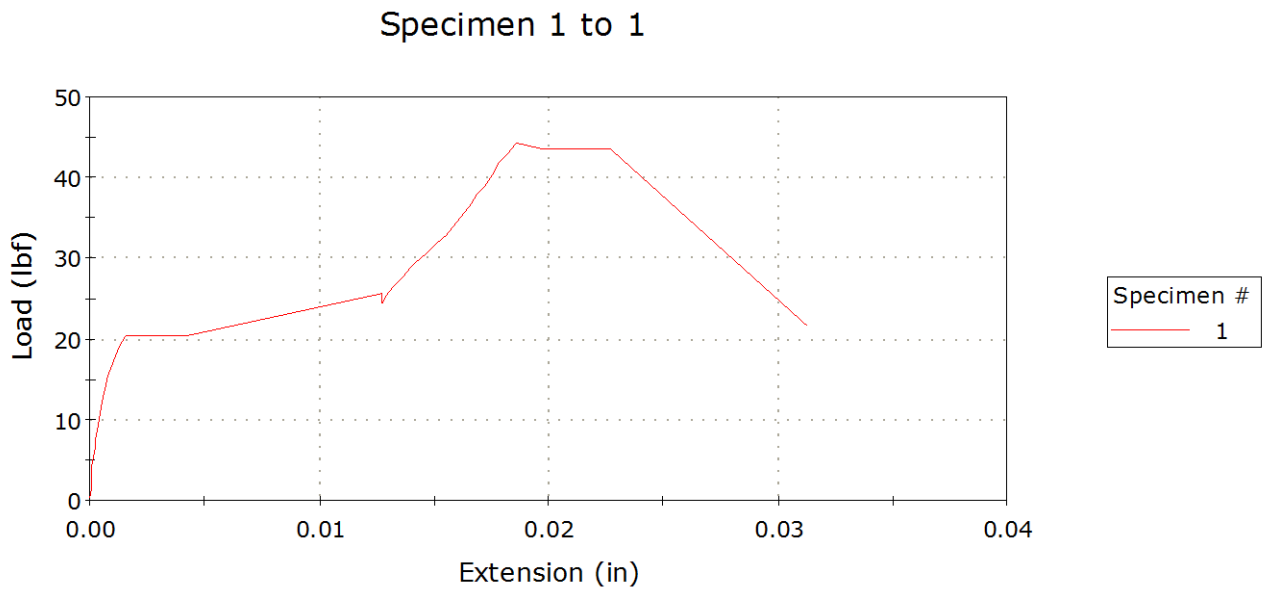
	Tensile stress at Break (Standard) (psi)	Modulus (E-modulus) (psi)	Tensile stress at Yield (Offset 300 %) (psi)	Load at Break (Standard) (lbf)
1	492.63847	-----	-----	21.59003
Mean	492.63847	-----	-----	21.59003

	Extension at Break (Standard) (in)
1	0.03127
Mean	0.03127

Table 10: Instron Data

Export Raw Data : Export raw data	TRUE						
Results Table 1							
		Tensile st	Modulus (	Tensile st	Load at Br	Extension at Break (Standard)	
		(psi)	(psi)	(psi)	(lbf)	(in)	
	1	492.6385			21.59003	0.03127	
Mean		492.6385			21.59003	0.03127	

Raw Data From Bluehill

	A
1	Test Type,"Tension"
2	Method Name,"C:\Instron Data\Baja\Aluminum Insert to Carbon Fiber Tube\Tension Test Alu insert to Carbon Fiber Tube 150lbs-min.im_tens"
3	Sample name,"C:\Instron Data\Baja\Aluminum Insert to Carbon Fiber Tube\4-29-15\Carbon Fiber Tube.is_tens"
4	User,""
5	Sample note 1,""
6	Sample note 2,""
7	Sample note 3,""
8	Geometry,"Tubular"
9	Specimen,1
10	Specimen label,""
11	Width,0.751969,"in"
12	Thickness,0.008071,"in"
13	Length,4.350394,"in"
14	Diameter,0.393701,"in"
15	Inner diameter,0.314961,"in"
16	Outer diameter,0.393701,"in"
17	Wall thickness,0.039370,"in"
18	Area,0.282743,"cm^2"
19	Linear density,100.000000,"tex"
20	Sled weight,2.248089,"lbf"
21	Loading span,0.393701,"in"
22	Support span,3.937008,"in"
23	Span ratio,"2"
24	Fixture type,"4-point"
25	Included
26	Final width,0.393701,"in"
27	Final thickness,0.039370,"in"
28	Final length,3.937008,"in"
29	Final diameter,0.393701,"in"
30	Final Inner diameter,0.314961,"in"
31	Final outer diameter,0.393701,"in"
32	Final wall thickness,0.039370,"in"
33	Final area,0.282743,"cm^2"
34	Final linear density,100.000000,"tex"
35	Operator,"Amy Blake"
36	Custom text input 2,""
37	Custom text input 3,""
38	Custom text input 4,""
39	Custom text input 5,""
40	Custom text input 6,""
41	Custom text input 7,""
42	Custom text input 8,""
43	Custom text input 9,""
44	Custom text input 10,""
45	Custom text input 11,""
46	Custom text input 12,""
47	Custom text input 13,""
48	Custom text input 14,""
49	Custom text input 15,""
50	Custom text input 16,""
51	Custom text input 17,""
52	Custom text input 18,""
53	Custom text input 19,""
54	Custom text input 20,""
55	Custom number input 1,0.000000,""
56	Custom number input 2,0.000000,""
57	Custom number input 3,0.000000,""
58	Custom number input 4,0.000000,""
59	Custom number input 5,0.000000,""
60	Custom number input 6,0.000000,""
61	Custom number input 7,0.000000,""
62	Custom number input 8,0.000000,""
63	Custom number input 9,0.000000,""
64	Custom number input 10,0.000000,""
65	Time sec,"Extension in","Load lbf","Tensile stress ksi","Cycle Count ","Total Cycle Count ","Repetitions Count ","Tensile extension in","Tensile strain %","Displacement (Strain 1) in","Displacement (Strain 2) in"
66	0,2.353917e-006,0.2768883,0.006318001,0,0,0,2.353917e-006,5.410814e-005,0,0,5.410812e-005,2.353917e-006,1.255944,6.318004
67	0.5,4.707834e-005,1.485251,0.03389026,0,0,0,4.707834e-005,0.001082163,0,0,0.001082157,4.707834e-005,6.736986,33.89063
68	1,8.23871e-005,2.824523,0.0644496,0,0,0,8.23871e-005,0.001893785,0,0,0.001893767,8.23871e-005,12.81182,64.45082
69	1.5,0.0001247576,4.336503,0.09894976,0,0,0,0.0001247576,0.002867731,0,0,0.00286769,0.0001247576,19.67005,98.9526
70	2,0.0001765438,5.528952,0.1261589,0,0,0,0.0001765438,0.00405811,0,0,0.004058028,0.0001765438,25.07891,126.164
71	2.5,0.0002283299,6.777191,0.154641,0,0,0,0.0002283299,0.005248489,0,0,0.005248351,0.0002283299,30.74082,154.6492
72	3,0.0002942396,7.802192,0.1780294,0,0,0,0.0002942396,0.006763517,0,0,0.006763288,0.0002942396,35.39015,178.0414
73	3.5,0.0003672111,9.065984,0.2068664,0,0,0,0.0003672111,0.00844087,0,0,0.008440513,0.0003672111,41.12262,206.8839

73	3.5,0.0003672111,9.065984,0.2068664,0,0,0,0,0.0003672111,0.00844087,0,0,0.008440513,0.0003672111,41.12262,206.8839
74	4,0.0004284129,10.41085,0.2375534,0,0,0,0.0004284129,0.00984768,0,0,0.009847196,0.0004284129,47.22283,237.5768
75	4.5,0.0004896147,11.83999,0.2701633,0,0,0,0.0004896147,0.01125449,0,0,0.01125386,0.0004896147,53.7053,270.1938
76	5,0.0005743558,13.1416,0.2998633,0,0,0,0.0005743558,0.01320239,0,0,0.01320151,0.0005743558,59.60929,299.9029
77	5.5,0.0006755742,14.11277,0.3220234,0,0,0,0.0006755742,0.01552904,0,0,0.01552783,0.0006755742,64.01447,322.0734
78	6,0.0007862082,15.44887,0.3525103,0,0,0,0.0007862082,0.01807212,0,0,0.01807048,0.0007862082,70.07492,352.574
79	6.5,0.0009227355,16.57921,0.3783022,0,0,0,0.0009227355,0.02121039,0,0,0.02120814,0.0009227355,75.20204,378.3825
80	7,0.001096925,17.83859,0.4070385,0,0,0,0.001096925,0.02521439,0,0,0.02521121,0.001096925,80.91447,407.1411
81	7.5,0.001320547,19.03959,0.4344427,0,0,0,0.001320547,0.03035466,0,0,0.03035006,0.001320547,86.36212,434.5746
82	8,0.001612433,20.31863,0.4636277,0,0,0,0.001612433,0.03706407,0,0,0.03705721,0.001612433,92.16375,463.7996
83	8.5,0.004307668,20.51198,0.4680396,0,0,0,0.004307668,0.09901789,0,0,0.0989689,0.004307668,93.04078,468.5031
84	9,0.01271821,25.73074,0.5871206,0,0,0,0.01271821,0.2923463,0,0,0.2919198,0.01271821,116.7127,588.837
85	9.5,0.01278412,24.37397,0.5561621,0,0,0,0.01278412,0.2938613,0,0,0.2934303,0.01278412,110.5585,557.7965
86	10,0.01290417,25.37477,0.5789982,0,0,0,0.01290417,0.2966208,0,0,0.2961818,0.01290417,115.098,580.7157
87	10.5,0.01325491,26.59617,0.6068678,0,0,0,0.01325491,0.3046829,0,0,0.3042197,0.01325491,120.6382,608.7168
88	11,0.01367861,27.91379,0.6369332,0,0,0,0.01367861,0.3144224,0,0,0.3139291,0.01367861,126.6148,638.9358
89	11.5,0.01409996,29.13576,0.664816,0,0,0,0.01409996,0.3241077,0,0,0.3235836,0.01409996,132.1576,666.9707
90	12,0.01458958,30.2725,0.690754,0,0,0,0.01458958,0.3353622,0,0,0.3348011,0.01458958,137.3138,693.0705
91	12.5,0.01503447,31.68715,0.7230331,0,0,0,0.01503447,0.3455887,0,0,0.3449929,0.01503447,143.7305,725.5318
92	13,0.01551702,32.81775,0.7488312,0,0,0,0.01551702,0.3566808,0,0,0.3560462,0.01551702,148.8588,751.5021
93	13.5,0.01591483,34.12279,0.7786092,0,0,0,0.01591483,0.3658251,0,0,0.3651576,0.01591483,154.7784,781.4576
94	14,0.01622555,35.29866,0.8054403,0,0,0,0.01622555,0.3729674,0,0,0.3722736,0.01622555,160.1121,808.4443
95	14.5,0.01655981,36.46741,0.8321086,0,0,0,0.01655981,0.3806507,0,0,0.3799281,0.01655981,165.4134,835.276
96	15,0.01686346,37.76056,0.8616155,0,0,0,0.01686346,0.3876307,0,0,0.3868813,0.01686346,171.279,864.9554
97	15.5,0.01723773,38.91359,0.8879252,0,0,0,0.01723773,0.3962339,0,0,0.395451,0.01723773,176.5091,891.4435
98	16,0.0175461,40.36709,0.9210908,0,0,0,0.0175461,0.4033221,0,0,0.4025109,0.0175461,183.102,924.8058
99	16.5,0.01785211,41.84974,0.9549219,0,0,0,0.01785211,0.4103561,0,0,0.4095164,0.01785211,189.8273,958.8405
100	17,0.01822167,42.98742,0.9808812,0,0,0,0.01822167,0.4188511,0,0,0.4179764,0.01822167,194.9877,984.9897
101	17.5,0.01857947,44.18447,1.008195,0,0,0,0.01857947,0.4270755,0,0,0.4261662,0.01857947,200.4174,1012.501
102	18,0.01975407,43.59363,0.9947136,0,0,0,0.01975407,0.4540755,0,0,0.4530477,0.01975407,197.7374,999.2304
103	18.5,0.0227153,43.49708,0.9925106,0,0,0,0.0227153,0.5221435,0,0,0.5207851,0.0227153,197.2994,997.6929
104	18.662,0.03127179,21.59003,0.4926385,0,0,0,0.03127179,0.7188266,0,0,0.7162554,0.03127179,97.93074,496.1797

Full ANSYS Results and Mechanical Report

ANSYS MECHANICAL REPORT:

Contents

-

Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (A4)

Geometry

TABLE 2
Model (A4) > Geometry

Object Name	Geometry
State	Fully Defined
Definition	
Source	\\uanet.edu\ZIPSpace\A\amn39\Creo\ANSYS_files\dp0\SYS\DM\SYS.agdb
Type	DesignModeler
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	1.5621e-002 m
Length Y	1.5621e-002 m
Length Z	0.1778 m
Properties	
Volume	2.4802e-005 m³

Mass	0.1947 kg
Scale Factor Value	1.
Statistics	
Bodies	3
Active Bodies	3
Nodes	7086
Elements	2438
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\amn39\AppData\Local\Temp
Analysis Type	3-D
Decompose Disjoint	Yes

Geometry			
Enclosure and Symmetry Processing	Yes		

TABLE 3
Model (A4) > Geometry > Parts

Object Name	*TRM_SRF*	*TRM_SRF*	*TRM_SRF*
State	Meshed		
Graphics Properties			
Visible	Yes		
Transparency	1		
Definition			
Suppressed	No		
Stiffness Behavior	Flexible		
Coordinate System	Default Coordinate System		
Reference Temperature	By Environment		
Material			
Assignment	Structural Steel		
Nonlinear Effects	Yes		
Thermal Strain Effects	Yes		
Bounding Box			
Length X	1.5621e-002 m		
Length Y	1.5621e-002 m		
Length Z	5.08e-002 m		0.127 m
Properties			
Volume	7.9572e-006 m³		8.8876e-006 m³
Mass	6.2464e-002 kg		6.9768e-002 kg

Centroid X	1.4622e-018 m	-2.7852e-019 m	-3.8963e-020 m
Centroid Y	-3.9107e-007 m		-1.7507e-006 m
Centroid Z	0.12984 m	-2.837e-003 m	6.35e-002 m
Moment of Inertia Ip1	1.3679e-005 kg·m²		9.5056e-005 kg·m²
Moment of Inertia Ip2	1.3679e-005 kg·m²		9.5056e-005 kg·m²
Moment of Inertia Ip3	1.6196e-006 kg·m²		3.446e-006 kg·m²
Statistics			
Nodes	1923	1869	3294
Elements	1006	964	468
Mesh Metric	None		

Coordinate Systems

TABLE 4
Model (A4) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0.
Origin	
Origin X	0. m
Origin Y	0. m
Origin Z	0. m
Directional Vectors	
X Axis Data	[1. 0. 0.]
Y Axis Data	[0. 1. 0.]
Z Axis Data	[0. 0. 1.]

Connections

TABLE 5
Model (A4) > Connections

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

TABLE 6
Model (A4) > Connections > Contacts

Object Name	*Contacts*
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0.
Tolerance Value	4.4792e-004 m
Use Range	No
Face/Face	Yes
Face/Edge	No
Edge/Edge	No
Priority	Include All

Group By	Bodies	
Search Across	Bodies	

TABLE 7
Model (A4) > Connections > Contacts > Contact Regions

Object Name	*Contact Region*	*Contact Region 2*
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Contact	3 Faces	
Target	3 Faces	
Contact Bodies	TRM_SRF	
Target Bodies	TRM_SRF	
Definition		
Type	Bonded	
Scope Mode	Automatic	
Behavior	Program Controlled	
Trim Contact	Program Controlled	
Trim Tolerance	4.4792e-004 m	
Suppressed	No	
Advanced		
Formulation	Program Controlled	
Detection Method	Program Controlled	
Penetration Tolerance	Program Controlled	
Elastic Slip Tolerance	Program Controlled	
Normal Stiffness	Program Controlled	
Update Stiffness	Program Controlled	

Pinball Region	Program Controlled
Geometric Modification	
Contact Geometry Correction	None

Mesh

TABLE 8
Model (A4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off
Relevance Center	Coarse
Element Size	Default
Initial Size Seed	Active Assembly
Smoothing	Medium
Transition	Fast
Span Angle Center	Fine
Minimum Edge Length	1.955e-002 m
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2

Inflation Algorithm	Pre
View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Patch Independent Options	
Topology Checking	Yes
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	7086
Elements	2438
Mesh Metric	None

Static Structural (A5)

TABLE 9
Model (A4) > Analysis

Object Name	*Static Structural (A5)*
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

TABLE 10
Model (A4) > Static Structural (A5) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off

Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Analysis Data Management	
Solver Files Directory	C:\Users\amn39\Desktop\Analysis1_files\dp0\SYS\MECH\
Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	No

Solver Units	Active System	
Solver Unit System	mks	

TABLE 11
Model (A4) > Static Structural (A5) > Loads

Object Name	*Force*	*Fixed Support*
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	1 Face	
Definition		
Type	Force	Fixed Support
Define By	Components	
Coordinate System	Global Coordinate System	
X Component	0. N (ramped)	
Y Component	0. N (ramped)	
Z Component	1500. N (ramped)	
Suppressed	No	

FIGURE 1
Model (A4) > Static Structural (A5) > Force

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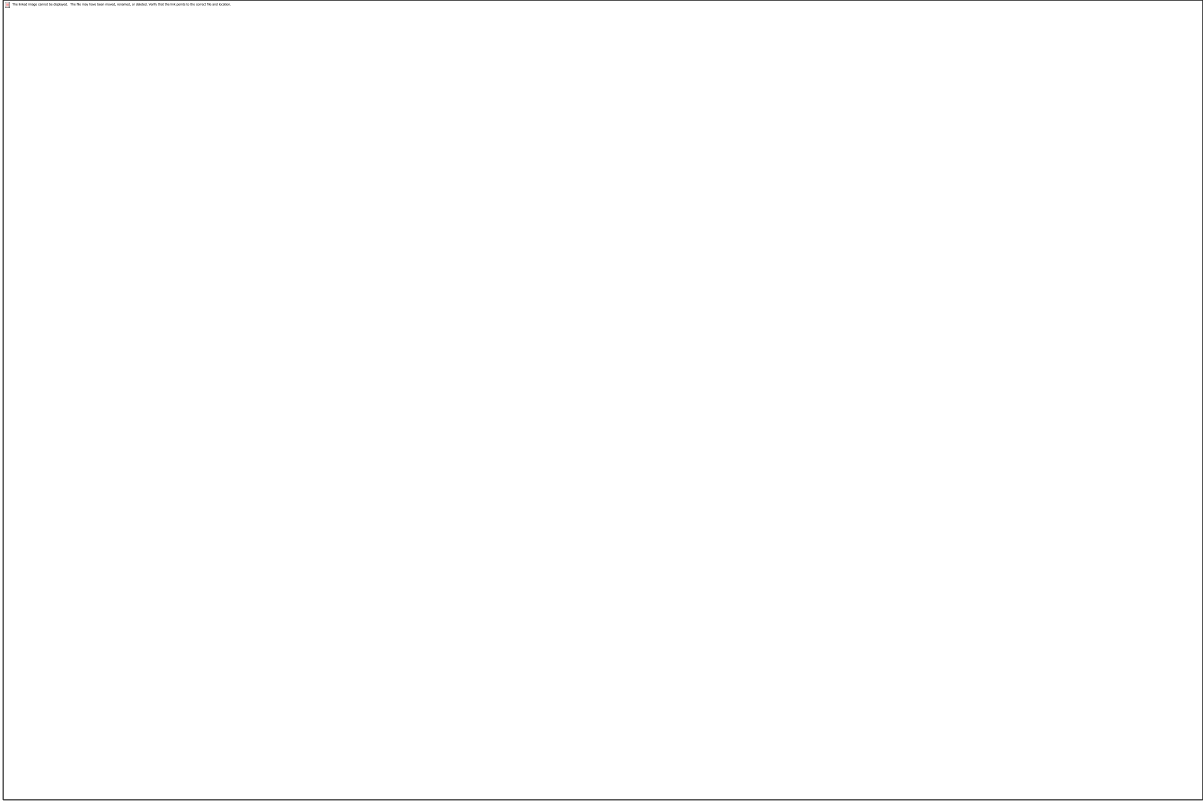
Solution (A6)

TABLE 12
Model (A4) > Static Structural (A5) > Solution

Object Name	Solution (A6)
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done

TABLE 13
Model (A4) > Static Structural (A5) > Solution (A6) > Solution Information

Object Name	Solution Information
State	Solved

Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 14
Model (A4) > Static Structural (A5) > Solution (A6) > Results

Object Name	*Equivalent Stress*
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Equivalent (von-Mises) Stress
By	Time
Display Time	Last
Calculate Time History	Yes
Identifier	

Suppressed	No
Integration Point Results	
Display Option	Averaged
Average Across Bodies	No
Results	
Minimum	1.3766e+006 Pa
Maximum	2.4171e+007 Pa
Minimum Occurs On	TRM_SRF
Maximum Occurs On	TRM_SRF
Minimum Value Over Time	
Minimum	1.3766e+006 Pa
Maximum	1.3766e+006 Pa
Maximum Value Over Time	
Minimum	2.4171e+007 Pa
Maximum	2.4171e+007 Pa
Information	
Time	1. s
Load Step	1
Substep	1
Iteration Number	1

Material Data

Structural Steel

TABLE 15
Structural Steel > Constants

Density	7850 kg m^-3

Coefficient of Thermal Expansion	1.2e-005 C^-1
Specific Heat	434 J kg^-1 C^-1
Thermal Conductivity	60.5 W m^-1 C^-1
Resistivity	1.7e-007 ohm m

TABLE 16
Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength Pa
0

TABLE 17
Structural Steel > Compressive Yield Strength

Compressive Yield Strength Pa
2.5e+008

TABLE 18
Structural Steel > Tensile Yield Strength

Tensile Yield Strength Pa
2.5e+008

TABLE 19
Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
4.6e+008

TABLE 20
Structural Steel > Isotropic Secant Coefficient of Thermal Expansion

Reference Temperature C
22

TABLE 21
Structural Steel > Alternating Stress Mean Stress

Alternating Stress Pa	Cycles	Mean Stress Pa
3.999e+009	10	0

2.827e+009	20	0
1.896e+009	50	0
1.413e+009	100	0
1.069e+009	200	0
4.41e+008	2000	0
2.62e+008	10000	0
2.14e+008	20000	0
1.38e+008	1.e+005	0
1.14e+008	2.e+005	0
8.62e+007	1.e+006	0

TABLE 22
Structural Steel > Strain-Life Parameters

Strength Coefficient Pa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient Pa	Cyclic Strain Hardening Exponent
9.2e+008	-0.106	0.213	-0.47	1.e+009	0.2

TABLE 23
Structural Steel > Isotropic Elasticity

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	2.e+011	0.3	1.6667e+011	7.6923e+010

TABLE 24
Structural Steel > Isotropic Relative Permeability

Relative Permeability
10000