Abstract

LANEY, MATTHEW LANGFORD. Sustainable Composites from Natural Materials. (Under the Direction of Dr. Abdel-Fattah M. Seyam and Dr. Timothy G. Clapp).

Although usually unnoticed, composites have become important parts of everyday life for most people. The most simplistic of structures such as mud bricks as well as naturally occurring composites like wood have been around for thousands of years. Today a working definition of a composite would be that composite materials are characterized by being multiphase materials within which the phase distribution and geometry has been tailored to optimize one or more properties [1]. The optimization of properties is achieved by different combinations of reinforcement and matrix materials which alters the composite material as a whole. Within composites there are subgroups named based on the matrix material used in consolidation of the composite structures [2]. Current commercial composites rely heavily on the petroleum industry having both reinforcement and matrix materials based on petroleum by-products. With this heavy reliance on petroleum much research is being done in alternatives for composite constituents. As well as increasing fuel prices there is much pressure from environmental groups and government agencies to seek other means for composites with more environmentally friendly processing and materials. Natural materials for reinforcement such as wood, kenaf, hemp, flax, jute, henequen, pineapple leaf, sisal, etc. and resins such as polylactide, cellulosic plastics, starch plastics, polyhydroxyalkanoates, and soy plastics have shown great potential in composites research. The research in composites from natural materials is challenging due to the significant difference in natural and synthetic fibers properties including surface properties and non-uniformity in length and linear density within and between natural

fibers, crimp, etc. To our knowledge none of the research in natural composites has taken advantage of 3D weaving and Vacuum Assisted Resin Transfer Molding (VARTM) technologies. This has prompted the undertaking of a systematic research program aimed at the development of composite structures from natural materials using these techniques. A range of three-dimensional (3D) woven preforms from 100% cotton fibers were constructed with different number of layers (thickness), x-yarn density, and weave structures. The samples were tested for their performance in terms of tensile, flex and impact properties.

Sustainable Composites from Natural Materials

by
Matthew Langford Laney

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APPROVED BY:

_____	_____
Dr. Abdel-Fattah Seyam Chair of Advisory Committee	Dr. Timothy Clapp Co-Chair of Advisory Committee
_____	_____
Dr. Mansour H. Mohamed Member of Advisory Committee	Dr. Tom Theyson Member of Advisory Committee

Dedication

Dedicated to my grandmother Mrs. E.S. Schumpert, my parents Richard and Susan Laney, and my brother and sister for their unconditional support over the past two years.

Biography

Mr. Matthew Laney was born on January 28th 1986 in Rocky Mount, NC. He graduated high school from Rocky Mount High School in Rocky Mount. He received his Bachelor's degree in Textile Technology from North Carolina State University in Fall 2008. In the Spring of 2009 he continued on to pursue a Master's of Science in Textiles under the guidance of Dr. Abdel-Fattah M. Seyam and Dr. Timothy G. Clapp.

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1. Introduction and Literature Review

Although usually unnoticed, composites have become important parts of everyday life for most people. The most simplistic structures such as the bricks made in the most remote villages of straw and mud are considered composites. Structures such as these have been around for thousands of years. There are as well naturally occurring composites such as wood and even teeth that fit under the most general definition of a composite. This definition is best described as a structure comprised of two or more constituent materials with different properties that ultimately stay separate from one another within the final assembly. The constituent materials are classified as reinforcement or matrix materials. The reinforcement materials serve as the 'backbone' or foundations for the composite while the matrix is added to affix the reinforcement and keep it in place. As the composite industry has changed so has the definition and classifications. Today a better working definition of a composite would be that composite materials are characterized by being multiphase materials within which the phase distribution and geometry has been tailored to optimize one or more properties [1]. Although this revised definition still covers a wide range of materials its most accepted classification can be divided into three subcategories. The composite formed by combining the two materials has far greater physical properties than either of the individual constituents. This is achieved by a behavior known as load transfer. This allows for the optimization of properties by applying different combinations of reinforcements and matrix materials. Because in most cases the reinforcement is malleable, the composite can also be shaped before combining the resin allowing for molded parts to be manufactured. These subgroups are named based on the matrix material used in consolidation of the composite structures [2]. These categories are known as:

- Polymer Matrix Composites (PMC)
- Metal Matrix Composites (MMC)
- Ceramic Matrix Composites (CMC)
- Carbon Carbon Composites (C/C)

Of the three major groups of composites the most common are PMCs. Although the other two types of composites are used in industry the mechanical properties and ease of manufacture of PMCs have allowed their spread into many markets. The most popular forms of PMCs use fiber reinforcement to provide strength to the structure. Many constructions of fibers are being used in composites such as braided, woven, knitted, and nonwoven mats. Since the development of high-modulus filaments and whiskers in the 60s there has been much research being done for advanced composites [3]. Of the three major groups of composite matrix systems polymers are the most complex structurally. While polymers are more complex than metal and ceramic matrix they also have a lower strength and are more vulnerable to ultraviolet light and other solvents, but are more resistant to chemical degradation [4]. The strength of the polymer matrix is improved using the fiber reinforcement allowing for mechanical properties surpassing that of metals or ceramics.

1.1 Fiber Reinforced Composites

Polymer Matrix Composites or PMCs most commonly use fiber reinforcements and a polymer resin. Fiber-reinforced composites are the most commonly used in high performance applications

at this time. The basic strength of these composite structures comes from the strength of the reinforcement fibers. By increasing the strength of the "backbone" of the structure the structure itself is strengthened. Over the last fifty years major advances have been made in the fiber sciences. The development and research of what is known to most as "high-performance" fibers has changed the textile industry greatly. Fiber Reinforced Composites or Polymer Matrix Composites have made their way into many markets since their early development.

In the early stages of advanced composites PMCs were readily found in the marine and aerospace industries. These forms of composites used glass fibers and nylon as their structural base or reinforcement. Nylon was quickly replaced by other fibers with new developments in fiber chemistry while fiber-glass continued to be researched and refined. The advancements in high-performance synthetic fibers began the expansion of the composites market. While in the early development stages the fibers such as Kevlar®, Nomex, and Twaron were limited because of high cost of production. The development of these fibers was fueled by increasing the mechanical properties as to compete with other materials such as metals and ceramics [5]. While the properties of the early composites were not exceptional they did have advantages over the conventional metal and ceramic materials. The fabrication of PMCs is much easier than that of MMCs or CMCs. The processing has much lower temperatures as well as requiring lower processing pressure [6]. Polymer Matrix composites also have much simpler machinery. For these reasons the development of PMCs was rapid expeditious and soon the use of PMCs began to be accepted in many structural applications where only metals were used prior [5].

1.2 Composite Applications

1.2.1 Armor

Ballistic protection has been in development since the first projectile weapon was invented. Much of what is used today has textiles incorporated in more ways than one. The major area where textiles are being used is in soft body armor. Soft armor is using 3D woven fabrics to provide ballistic protection and comfort. Hard armor applications also use composite structures but are usually combined with an impact face of ceramic material. Depending on the type of force trying to be stopped depends on the material used in the armor. While all armor is designed to eliminate penetration of projectiles, the basic job of armor is to deflect the projectiles and disperse the energy so that the body does not take full impact. The woven applications are exceptional in dispersing energy without as much damage to the structure as ceramic plate based armor. When absorbing impact a ceramic plate will crack and shatter to allow the energy to travel across the plate. Woven structures will allow the energy to travel through the fibers/yarns impacted to the crossover points in the structure where the energy is then diverted into other numerous fibers/yarns at these crossover points [5]. This is the reaction that takes place at one layer while most armor is made up of multiple layers. Multiple layers can see effects from the initial impact. The top layers will sometimes shear yarns to absorb the energy. This shearing (cutting) of the yarns happens under high impact force, but it also absorbs greater amounts of energy than the dispersion along the fiber length [4].

Using the 3D weaving technology composite helmet designs have been developed and woven to protect the cranium. To keep the shape these structures must have a matrix resin applied while much of the soft armor does not use resin.

1.2.2 Aerospace

Within the field of aerospace many different types of aircraft are covered. Composites have become incorporated into every area within this industry. Composites have been used in numerous applications in planes, helicopters, spacecraft, satellites and many others. Two of the major places composites are used in aerospace are spacecraft (space shuttles and satellites) as well as military aircraft (fighter planes and helicopters) because of their high demand for performance. In order to improve aircraft performance materials must be reduced in weight and have increased strength properties. As mentioned earlier, composites have been able to successfully help the advance of aerospace design to increase performance. Currently aircraft used by the military such as the F-22 are composed of over one third composite material [1]. Military fighter aircraft must be able to withstand very high pressures produced by wind resistance as well as high temperatures produced by the engines, but spacecraft push the limits of these properties even more. The structures used in spacecraft have to be able to withstand high vacuum pressures, radiation, as well as extremely wide temperature ranges from subzero temperatures while in orbit and temperatures reaching up to 1,650 ˚C during reentry. Currently to produce the composites that can withstand such strains autoclave molding is most popular. Research developments in grid structures and Z-reinforcements using resin infusion molding will replace the slow and expensive process of autoclave molding [1]. This will increase productivity as well as produce a material with a weight saving of up to 30% over the autoclaved composites. In Table 1 exhibits a general break down of the applications within the aerospace industry and where the fibers are used based on their properties.

Table 1 Properties of Aerospace Fibers [71]

Table 2. Reinforcing fibres commonly used in aerospace applications.

Fibre	Density (g/cc)	Modulus (GPa)	Strength (GPa)	Application areas
Glass				
E-glass	2·55	65–75	2·2–2·6	Small passenger a/c parts, aircraft interiors, secondary parts; Radomes; rocket motor casings
S-glass	2·47	85–95	4·4–4·8	Highly loaded parts in small passenger a/c
Aramid				
Low modulus	1·44	80–85	2·7–2·8	Fairings; non-load bearing parts
Intermediate modulus	1·44	120–128	2·7–2·8	Radomes, some structural parts; rocket motor casings
High modulus	1·48	160–170	2·3–2·4	Highly loaded parts
Carbon				
Standard modulus (high strength)	1·77–1·80	220–240	3·0–3·5	Widely used for almost all types of parts in a/c, satellites, antenna dishes, missiles, etc
Intermediate modulus	1·77–1·81	270–300	5·4–5·7	Primary structural parts in high performance fighters
High modulus	1·77–1·80	390–450	2·8–3·0 4·0–4·5	Space structures, control surfaces in a/c
Ultra-high strength	1·80–1·82	290–310	7·0–7·5	Primary structural parts in high performance fighters, spacecraft

1.2.3 Automotive

The automotive industry much like that of aerospace seeks high performance with high strength to weight ratio. The automotive industry has begun using fiber-reinforced composites to do just that. Although the stresses and temperatures are nowhere near what a space shuttle would encounter strength and weight are just as much a factor. Carbon fiber composites have made their way into the commercial car circuit therefore strength is of upmost importance. Carbon fiber is being used in body panels where fiberglass and sheet metal were used prior. As the performance of these cars increases the safety of the driver and passengers becomes even more

critical. The reasoning behind carbon fiber is not only the reduced weight of the vehicle but also its high strength and high thermal resistance. These characteristics of carbon fibers qualify them for providing the required performance for such applications. Composites have also been incorporated into many other applications in the race venue. In the formula one race series the cars have composite bodies as many other suspension and steering components such as struts and wishbones that see high loads. The brake rotors have also been developed using carbon based composites. Using carbon fiber has increased the life of the brake rotors because of increased thermal stability and better heat dispersion allowing the racers to use the brakes more without wearing them down. Composites have even found their way into NASCAR. The cars of NASCAR use a special piece called a splitter on the lower edge of the front bumper to increase down force on the nose of the car. The fiber used in this splitter was developed by Milliken and is called Tegris. Tegris is a 100% polypropylene fiber that is produced as a “tape yarn” or flat yarn.

1.3 Mechanical Properties of Composites

The properties of composites have proven much stronger in most cases than many other conventional materials such as steel or ceramics. The ability to achieve such improved properties comes from the ability to control aspects of the composite structure that directly affect the mechanical properties. The basis of this idea comes from the ability to change the matrix and reinforcement materials enabling a better or improved property to be achieved [6]. When changing these materials as well as the reinforcement structure or design allows the change in such behaviors as fiber volume fraction, fiber-matrix adhesion, fiber orientation, aspect ratio, and

fiber dispersion. The most important of these behaviors being the fiber-matrix adhesion which translates into the ability of the fiber and matrix to stick or stay attached to one another at the interface [7]. This ability directly affects the load transfer of the two materials as well as the processing of the composite. As well the fiber volume fraction is directly related to the strength of the composite. Due to the major impact of the properties of the constituent materials and their interaction the prediction of composite properties is important.

1.3.1 Property Prediction

There are numerous methods for predicting mechanical properties of composite structures. The most simplistic and commonly used is known as the rule of mixtures. This method can only be used when predicting the properties of continuous filament composites because it does not take into consideration factors such as fiber orientation, fiber dispersion, or interface interaction, that would take place with short fiber mats or other reinforcement structures containing multidirectional fibers. These factors which are essentially uncontrollable in manufacture make prediction of mechanical properties very difficult.

1.3.2 Fiber Volume Fraction

The fiber volume fraction (FVF) is important in predicting the mechanical properties for any type of composite. It can be found in most any modeling equations. The reason for this is its direct relationship to composite strength. The strength of the composite is higher at higher FVF which is rationalized by the strength of the fiber being greater than that of the matrix. Below a

certain point the FVF becomes too low and the matrix strength is greater and the composite strength declines. The critical fiber volume fraction is the optimal point at which the amount of fiber is great enough that its strength supersedes that of the matrix and the composite strength improves (Figure 1). This can also be explained by the interaction of the fiber and matrix during deformation. There are three basic phases a composite will go through during deformation (Figure 2). The first phase being the point at which the fibers and matrix deform elastically, at this point they will both share the load while deforming together. The next phase begins at the point where the matrix begins to deform plastically while the fibers continue to deform elastically and carry most of the loading. The third phase is the point at which the fibers fracture and the composite structure fractures directly after unless in some cases the fibers used will deform plastically [6,7].

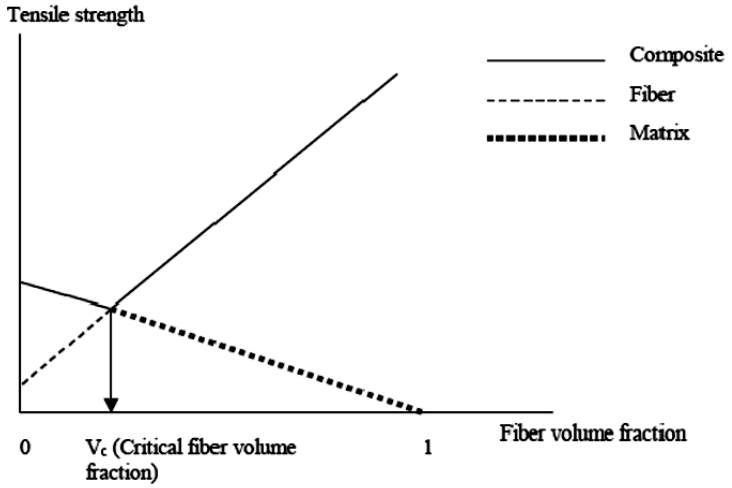


Figure 1 Composite tensile strength as function of FVF [9]

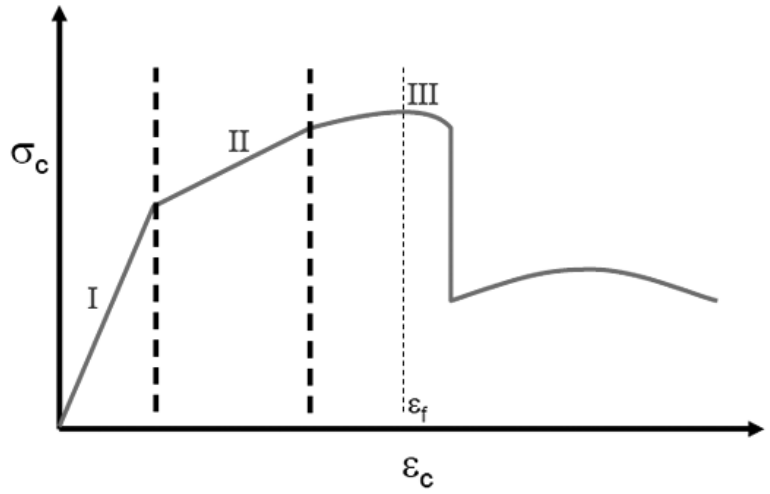


Figure 2 Phases of composite stress strain curve [9]

1.4 Fibers

Fiber-reinforced composites are the most commonly used in high performance applications at this time. The basic strength of these composite structures comes from the strength of the reinforcement fibers. By increasing the strength of the "backbone" of the structure, the structure as a whole gains strength. Over the last fifty years major advances have been made in the fiber sciences. The development and research of what is known to most as "high-performance" fibers has changed the textile industry greatly. One of the first synthetic fibers created was nylon which was developed in the 1940s. Much effort was put into developing this fiber because it was the first fiber that was created that melted before it degraded. Because of this characteristic nylon was able to be melt spun. Nylon is still widely used in the textile industry, but is not found as abundantly in the area of composites as it once was. The development of higher strength fibers have now taking its place in the market. Another fiber that was developed during the same time period that is still used in composites is fiberglass. Fiberglass was developed by Russell Games

Slayter in 1938 while he was working for Owens-Corning [8]. There are two major classifications of fiberglass: E-glass and S-glass. The E designation in E-glass denotes electrical. E-glass is used mainly in electrical applications because of its high resistivity. E-glass is lower cost than S-glass, or high strength glass, but also has a lower tensile strength than S-glass . S-glass is used in composites with higher strength requirements such as aerospace construction [9]. With the development of fiberglass more time and money was put into developing high tensile strength fibers. Another well-known high-performance material is carbon fiber that was developed initially by Dr. Roger Bacon when he heated rayon fibers until they carbonized. This process being very inefficient was refined and in the 1960s another method using poly-acrylonitrile was developed and became the primary method for production of carbon fibers. This process also was refined and went from producing fibers of only 55% carbon to 90-95% carbon. There are now other methods to produce lower grade carbon fiber using pitch or rayon, but their % carbon is greatly reduced. In Table 2 one can see the similarities in the actual strength of the fiberglass and carbon fiber while there is an adequate difference in the modulus of the two fiber types. This difference can be attributed to the higher orientation of the carbon fiber. All of these developments in fibers have helped the composite industry grow by increasing the efficiency of production of the composite reinforcement. In turn the composites have been able to decrease production costs and allowed increasing availability and expansion into other markets.

The alignment of the molecules of the fibers was directly related to the tensile strength of the fibers and the modulus. As the molecules become more oriented (parallel) with the fiber axis give the fiber an increased strength and a higher modulus in the oriented direction. When these

filaments are produced initially the molecules are in a somewhat random order. To help align the molecules the filaments go through a drawing process [2]. To achieve almost perfect orientation the molecule chains need to be initially oriented as well. In the late 1960s it was discovered that poly-benzamide and poly-phenylene terephthalamide could be processed into fibers that contained highly oriented, extended molecular chains [9]. DuPont used this research in aromatic polyamides (aramids) and became the first to produce a meta-aramid fiber known as Nomex. Many other chemical companies soon developed their own version of Nomex such as Teijinconex by Teijin and New Star produced by Yanti. Soon after the release of Nomex, DuPont released a para-aramid called Kevlar. Just as others followed Nomex the same happened for Kevlar and one well known fiber was produced named Twaron. The rights to Twaron are now owned by Teijin. The aramid based fibers are known for their high degree of orientation which gives them extraordinary strength, but these aramid fibers do have a drawback. The chemical structure of meta and para-aramids degrade when exposed to ultraviolet light. There are other fibers being researched to help eliminate this degradation such as Tegris and M5.

Table 2 Mechanical Properties of Some Fibers, Including Projections for M5® [4]

Fiber	Strength (σ) (GPa)	Failure Strain (ε) (%)	Modulus (*E*) (GPa)
600-den. Kevlar KM2	3.40	3.55	82.6
850-den. Kevlar KM2	3.34	3.80	73.7
840-den. Kevlar 129	3.24	3.25	99.1
1,500-den. Kevlar 29	2.90	3.38	74.4
200-den. Kevlar 29	2.97	2.95	91.1
1,000-den. Kevlar 29	2.87	3.25	78.8
1,140-den. Kevlar 49	3.04	1.20	120
Carbon fiber	3.80	1.76	227
E-glass	3.50	4.70	74.0
Nylon	0.91	N/A	9.57
M5 conservative	8.50	2.50	300
M5 goal	9.50	2.50	450
M5 (2001 sample)	3.96	1.40	271

Another advancement in the fiber sciences area are pre impregnated (or prepreg for short) fibers. Prepreg fibers are produced with the polymer resin already injected in the fiber structure. By adding the resin to the fiber during fiber production it is easier to control the volume of resin added to the fiber. This process also has an increased stiffness of 20-30% over conventional laminate processes. Being able to control the resin better saves money because less resin is wasted and the final structure is more uniform because the low percent of deviation in the amount of resin added to the fibers.

1.5 Matrix Material

The matrix materials used in advanced PMCs can be separated into two major groupings known as thermosetting and thermoplastics resins. These matrix materials have numerous purposes other than binding the structure together. The matrix within a composite does help in binding the reinforcement fiber together and keeping fibers oriented but also it transfers the load between fibers, protects the fibers from environmental and chemical elements, and can increase thermal properties depending on the type of resin used [10].

1.5.1 Thermosets

Thermosetting polymers, also known as thermosets, are estimated at making up over three quarters of all PMCs matrices. Thermosets are resin that readily cross-link during curing. Curing is caused by the addition of heat and pressure or the use of a catalyst which cause hardening of the resin. Covalent bonds for between the polymer chains which pulls them together and restricts their movement. The restricted movement of the bonded polymer chains increases the glass transitions temperature to above room temperature which makes thermosets very brittle at room temperature [11]. Although brittle at low temperatures thermosets have a higher softening temperature which allows them to be used in high temperature applications. Along with the brittleness thermosets are also very sensitive to water and have a very slow manufacturing technology. There has been effort to improve on these properties but with improvements of one the others suffered. Prepreg fibers or pre impregnated fibers were developed and helped in improving all aspects of the epoxy resin composites together [12]. Using Prepreg fibers

improved the problems seen in the toughness (brittle) and gave more resistance to water while improving the manufacturing speeds. These thermosets still could not compete with the properties provided by thermoplastic composites.

1.5.2 Thermoplastics

Thermoplastics make up only a small part of the PMC market. The replacement of thermosets with thermoplastics will most likely not happen anytime in the near future, but they do currently offer potential advantages over thermosets [13]. The basis of a thermoplastic is the ability to flow under stress at elevated temperature and return to solid form retaining their shape at room temperature [5]. They are also able to be continually reheated and cooled unlike thermosets. As seen in Table 3 there are many benefits of thermoplastics over thermosets. Some of the major advantages are the indefinite shelf life of the thermoplastic as well as low moisture absorption, high toughness, excellent thermal stability and exceptional damage tolerance [13]. Being semi-crystalline gives thermoplastics many of their advantages. Being semi-crystalline of containing amorphous regions within the polymer allows for the structure to provide some elasticity which makes the structures less brittle. The amorphous regions also allow for better flow above Tg (Glass Transition Temperature) during processing. The most well-known semi-crystalline thermoplastics are Polyethylene (PE), Polypropylene (PP), Polybutylene terephthalate (PBT), and Polyethylene terephthalate (PET).

Table 3 Benefits of Composites [5]

Lower manufacturing cost

- no cure
- unlimited shelf-life
- reprocessing possible (for repair and recycling)
- less health risks due to chemicals during processing
- low moisture content
- thermal shaping possible
- weldability (fusion bonding possible)

Better performance

- high toughness (damage tolerance)
- good hot/wet properties
- high environmental tolerance

The disadvantages of thermoplast-matrix composites include the following:

- limitations in processing methods
- high processing temperatures
- high viscosities
- stiff and dry prepregs when a solvent is not used (i.e., not drapeable or tacky)
- fiber surface treatments less developed

1.6 Natural Composites

As in many industries there has been a recent push for more environmentally friendly products. This is no different in the world of composites as concerns grow with recycling and landfills. The production of synthetic fibers is energy intensive as well as produces waste to be disposed of. Along with the fibers the polymer matrices used for most current high performance composites are by-products from the oil industry which is already struggling to produce sufficient quantities. Another driver of the green composites movement is the automotive industry which contributes largely to the composites found in landfills. Composites with natural fiber reinforce offer a sustainable alternative to current commercial composites. While they are a

good alternative there are performance constraints in current applications such as automotive, aerospace, construction as well as others that must be met to successfully integrate these 'natural composites'. There are many natural fibers as well as natural based polymers that are currently being used and investigated for application into natural fiber composites. In Figure 3 the classifications of the different natural fibers are divided by organic and inorganic as well as arranged by their host organism. Plant fibers make up the largest grouping of natural fibers and most commonly used of the plant fibers come from the seed or stem fibers known as dicotyledon. The dicotyledon fibers are used more often especially in the case of stem fibers because the vascular bundles of the stem are ring shaped which gives increased strength to the fibers derived from the plant stem. Flax, Hemp, Jute and Kenaf are some of the most well-known of the dicotyledon family also known as bast fibers. Some of the areas these fibers are currently being used in composites are found within the automotive industry in door and trunk trims as well as other interior parts. Large percentages of these composites still use thermosets and thermoplastic resins which makes them only partially eco-friendly [14]. Bio-composites, more specifically the coined 'green composites' contain both bio-fiber and bio-plastic therefore are expected to be biodegradable. In many cases the plastics derived from renewable resources are non-biodegradable, depending on structure and curing during fabrication [15]. In order to have a completely 'green composite' the composite must have both natural fiber reinforcement and a completely natural matrix or 'green' matrix material [16].

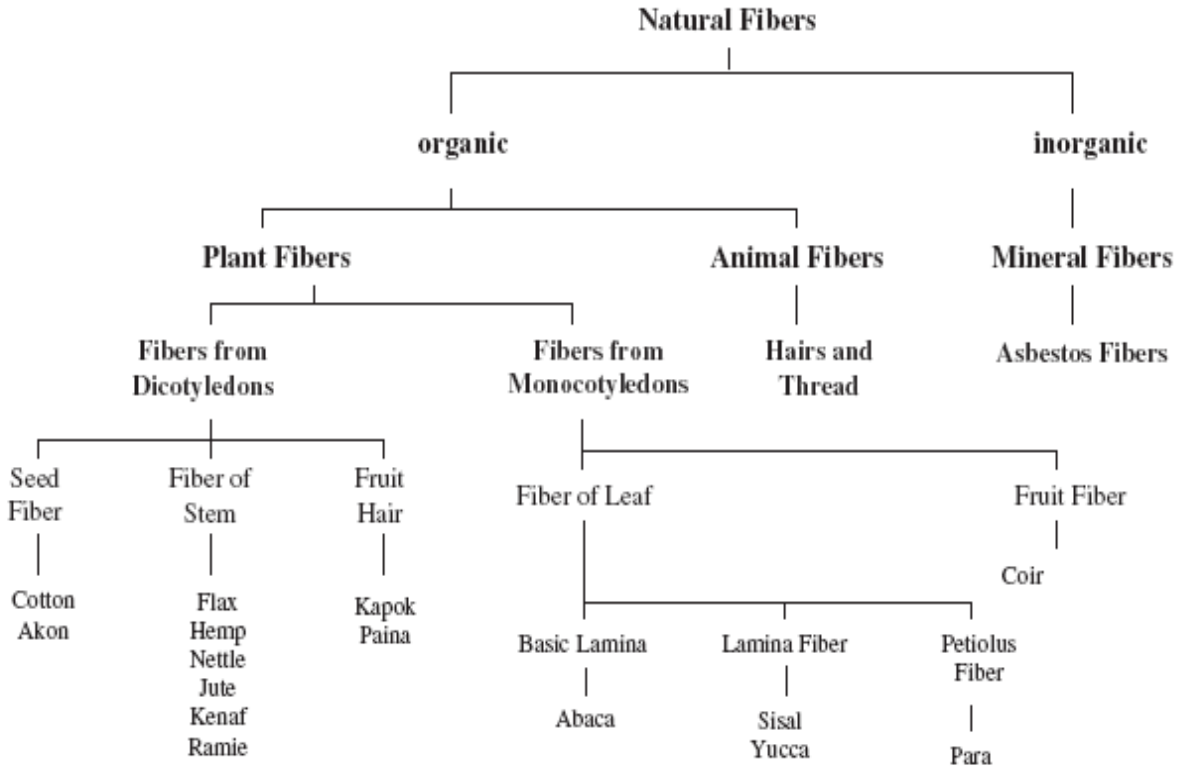


Figure 3 Classifications of natural fibers [16]

1.6.1 Biofibers

Plant fibers make up the largest grouping of natural fibers and most commonly used of the plant fibers come from the seed or stem fibers known as dicotyledon. The dicotyledon fibers are used more often especially in the case of stem fibers because the vascular bundles of the stem are ring shaped (Figure 4) which gives increased strength to the fibers derived from the plant stem. Flax, Hemp, Jute and Kenaf are some of the most known of the dicotyledon family also known as bast fibers.

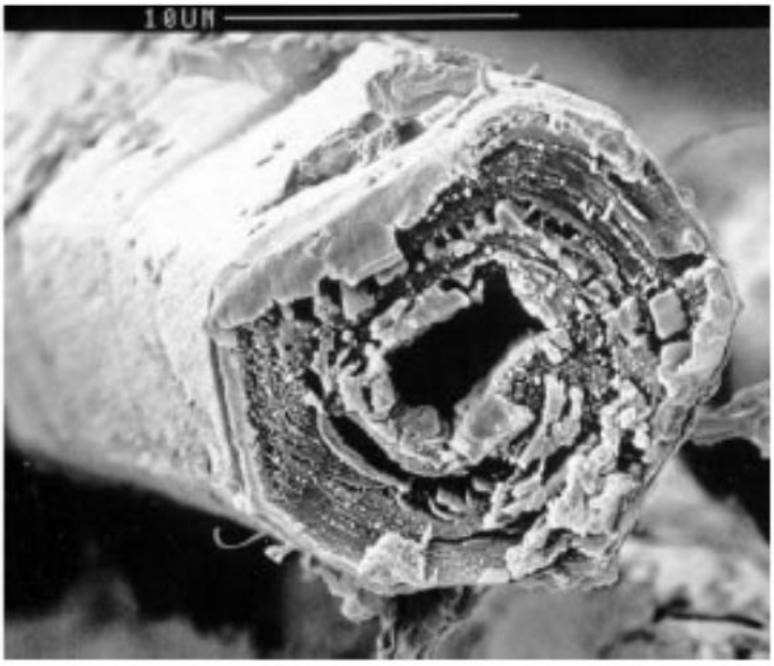


Figure 4 Cross-section of flax fiber [17]

Composites with natural fiber reinforce offer a sustainable alternative to current commercial composites. While they are a good alternative there are performance constraints in current applications such as automotive, aerospace, construction as well as others that must be met to successfully integrate these ‘natural composites’. As seen in Table 4 and Figures 5 and 6, the mechanical properties of some of these natural fibers are comparable to that of the generally accepted numbers for E-Glass.

Table 4 Comparison of Fiber Mechanical Properties [18]

Fibre type	Young's modulus (GPa)	Ultimate tensile strength (MPa)	Strain to failure (%)	Reference
E-Glass	76	2000	2.6	
HS carbon	230	3400	3.4	21
Kevlar™	130	3000	2.3	
Flax	–	814	–	22
	–	1500[a]	–	23
	103	690	–	24
	85	2000[a]	–	25
	50–70	500–900	1.3–3.3	26
	28	345–1035	2.7–3.2	27
	100	1100	2.4	28
	52	621	1.33	
Hemp	–	690	–	22
	25	895	–	29
	30–60	310–750	2–3	25
	–	690	1.6	27
	57	–	–	24
Jute	–	455	–	22
	8	538	–	29
	10–78	–	–	30
	27.6	393–773	1.7–1.8	26
	13	550	–	27

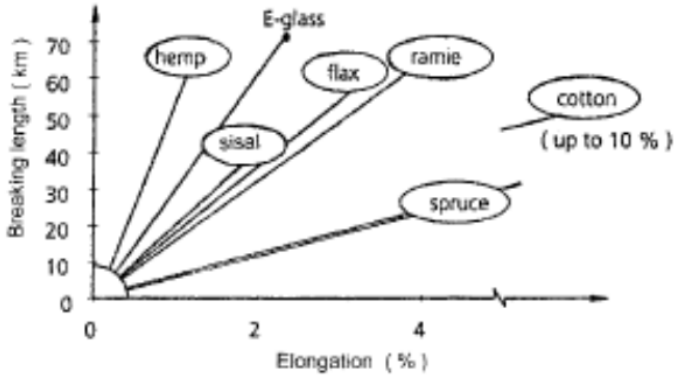


Figure 5 Break strength vs. elongation of common fibers [19]

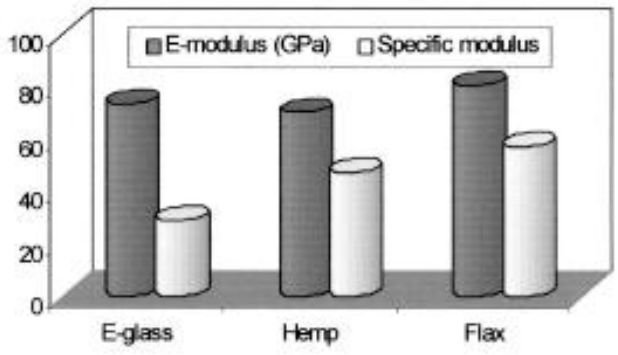


Figure 6 Specific modulus of fibers [18]

Some of the areas these fibers are currently being used in composites are found within the automotive industry in door and trunk trims as well as other interior parts. Large percentages of these composites still use thermosets and thermoplastic resins which makes them only partially eco-friendly [20, 21]. Bio-composites, more specifically the coined ‘green composites’ contain both bio-fiber and bio-plastic therefore are expected to be biodegradable. In many cases the plastics derived from renewable resources are non-biodegradable, depending on structure and curing during fabrication [21]. In order to have a completely ‘green composite’ the composite must have both natural fiber reinforcement and a completely natural matrix or ‘green’ matrix material [22].

1.6.2 Bioresins

Currently there is much research being directed toward the development and integration on matrix materials based on natural resources to create biodegradable resins. The sights are set on the ability to gain the mechanical properties of synthetic resins while maintaining the recyclable aspect of the natural based resins.

There are thermoplastics being used which are still not ‘green’ but are rather easily removed from the composite and can be recycled. Thermoplastic resins that meet this requirement such as Polypropylene will be heated past their Tm (melting temperature) and as the polymer becomes amorphous the temperatures are high enough to burn off the natural fibers. Although incineration is not environmental degradation in the case of thermoplastic resins it eliminates the process of reclaiming the natural fibers for disposal [21]. With the incineration of natural fibers the only waste produced is the release of carbon from the breakdown of the organic material and the amount of carbon released is only equivalent to the amount that the plant absorbed during its growth period.

To eliminate using incineration for recycling of natural composites much research has been done in the area of bio-based thermosetting resins using plant oils. The major plant oil being studied is that of the soybean. The soybean oil is mainly composed of triglyceride molecules and fatty acid that can be chemically functionalized to produce a cross-linked thermoset resin. Acrylated epoxidized soybean oil also known as AESO is an example of a commercialized soybean resin. Acrylic acid is reacted with the soybean oil seen in Figure 7 then blended with a co-monomer such as styrene to allow copolymerization [23]. The styrene reacts with the acrylated oil to induce cross-linking between the chains. The cross-linking gives rigidity to the structure giving the resin its mechanical properties.

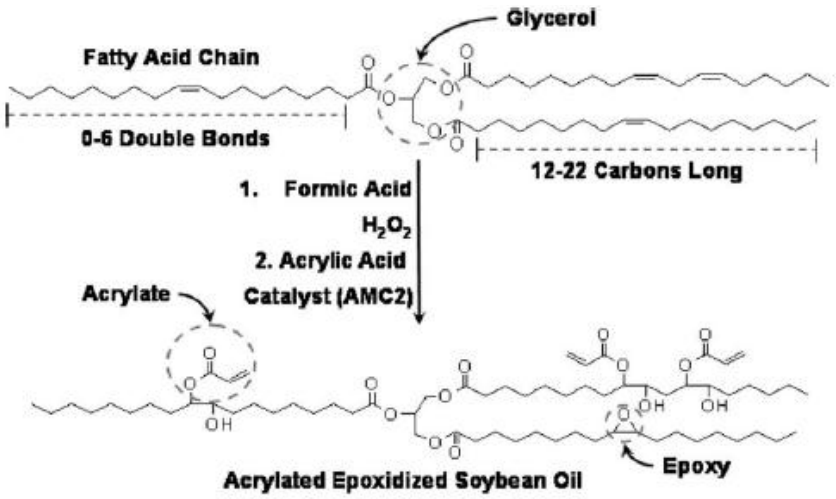


Figure 7 Chemical structure and reaction leading from triglyceride oil to acrylated epoxidized soybean oil [20]

Resin can be derived from other grains other than the soybean. The availability of the grains is a major factor in determining the use of natural based resins. The United States is one of the top producers of all of the four major grains giving an advantage in research. Although soybean is currently the most well-known commercially available natural based resin these other grains are continuously being researched to find other avenues for sustainable materials.

1.6.3 Driving Forces

The Green initiative had many driving forces that are pushing its success in industry. There are many apparent benefits to biocomposites other than the sole aspect of being environmentally friendly. Using natural fiber reinforcement in the composites alone provide low cost, lower weight, ease of recycling, availability, carbon dioxide neutrality, and improved thermal and acoustic insulation properties over most synthetic fiber based composites. Many directives have

been put in place by industry itself in order to improve the recyclability of products. A cost benefit has also been seen in using renewable and natural resources in place of current synthetics used in many products [24,25]. The largest push comes from the governments around the world. Many government legislations have been put into action to better control the processes of synthetics as well as limit the overall production using synthetics to achieve this environmental awareness.

1.6.4 Cost Benefit

The fiscal benefit in biocomposites can be seen throughout manufacture to end product. The difference in raw material cost shows the initial benefit of using natural fibers. In Table 5 the cost per kilogram of Jute, and Coir fibers are approximately 10 percent the cost of Glass fibers. This can be attributed to many different aspects required in producing these fibers. On average the energy consumption of producing natural fibers apposite for composites is 60 percent less than that of equivalent glass fibers.

Table 5 Cost per Kilogram of Common Fibers [19]

Fibre	Carbon	Steel	Glass	Sisal	Jute	Coir
Cost (US $/kg)	200	30	3.25	0.36	0.30	0.25
Modulus/cost (GPa kg/$)	2.0	6.7	21.5	41.7	43.3	20.0

1.6.5 Government Legislation

The U.S. and many European countries have established laws and regulations to encourage the production and use of natural based or biocomposites [19]. The principle being instituted of 'Producer Pays' is urging manufacturers to take be accountable for their products throughout their full life cycle. This responsibility reinforces the importance of all aspects of a product from raw material, through manufacture, all the way to the disposal of the end product at the end of its life. There are other initiatives being put in place also to construct guidelines for comparison of properties and production energy consumption. The U.S. government is promoting the Life Cycle Analysis (LCA) to allow for testing of products throughout their lifespan for quantifiable environmental and energy evaluation. Through the LCA initiative specific fibers have shown improved properties over others through testing. Based on these results companies have put their focus on improving current processes and developing new processes to meet needs of multiple markets.

Other directives have also been adopted by these governments that are product specific. The End of Life Vehicle (ELV) and Waste Electrical and Electronic Equipment Directive (WEEE) are examples of directives put in place to regulate and stimulate improvement in the recyclability of products [19, 26]. The ELV directive along with joint support of the European Council Directive of Landfill of Waste is forcing the auto industry to drastically improve the sustainability of new vehicle production. Starting in 2006 this initiative required the minimum percent weight of reusable and recoverable materials to be at least 85% per vehicle and by 2015 each vehicle will be required to be at least 95% recyclable per weight of the vehicle [27]. WEEE is pushing the

electronics industry to use more natural composites in casings for computers and cell phones for improved recyclability after disposal.

1.6.6 Current Markets

Currently many markets use composites for multiple different products. Initiatives and regulations have been put in place in many countries to push many markets toward more eco-friendly products and processing. The market sectors that use plastic resins for composites cover a majority of products. In Figure 8 the market breakdown shows the variety of areas that resins and composites are used. Currently the largest market using natural materials is the transportation sector.

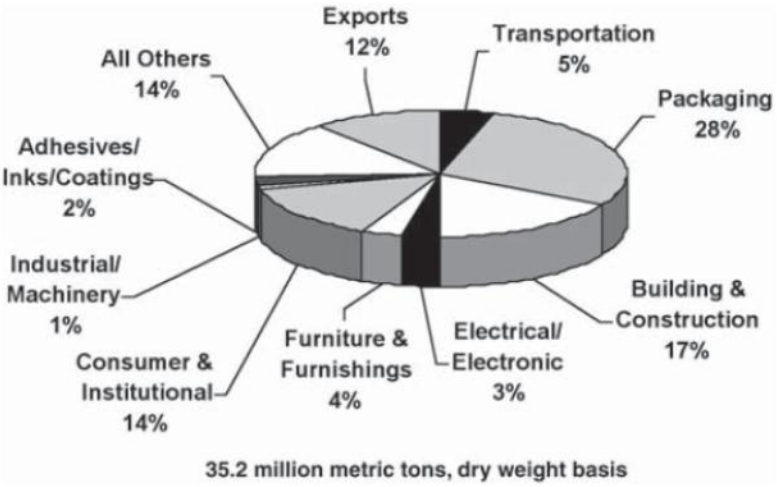


Figure 8 Market consumption of natural based resins and composites [28]

The auto industry has always been a large driving force behind the development of what are generally accepted as ‘biocomposites’. With advancements in biocomposites developed by the

auto industry in the 1990s the knowledge and performance have grown, attracting other markets to the idea of 'biocomposites' to replace synthetic fiber based composites. The production of synthetic fibers rely heavily on the petrochemical resources that are quickly depleting as well they produce harmful byproducts and large amounts of processing waste which are also a bearing force on the sustainability aspect of landfills [29,30]. Other markets such as the construction sector are currently using bio-composites as well. The industry has quickly grown and with increasing demand, faster production while maintaining similar properties has pushed the market to sustainable products. Decking, flooring, siding and railings are examples of products within the construction segment that have begun to use biocomposites successfully in the commercial market. While other markets and manufacturers are using more eco-friendly processing and natural and recyclable materials the auto industry is the most influential. The auto industry has involved other companies in the production of the composites. The processing involved in manufacturing biocomposite products is comparable to that of synthetic composites. Injection molding and extrusion can be used so no new techniques need to be developed for manufacture of actual final products [31]. By combining these technologies auto producers such as DaimerChrysler have been able to introduce large scale production lines using natural fibers. They recently started a line that produces exterior panels for the Mercedes A-class that consumes 40 metric tonnes of natural composites a year. Product lines such as Chryslers provide panels that reduce weight by approximately 7% and decrease costs by 5% from their synthetic counterparts [29].

1.7 Composite Molding Technologies

The stage of composite production in which the matrix is added and the composite structure is shaped is known as molding. There are numerous processes for binding the matrix to the fiber reinforcement. The development of these processes is still under research as composites continue to change. The processes currently used are hand lay-up, resin transfer, autoclaving, and vacuum infusion.

1.7.1 Hand Lay-Up

Hand lay-up is the original method of composite formation. The fiber reinforcement would be laid in a mold and the resin would be manually applied by using brushes or rollers also known as 'wet out'. This method has a very poor fiber to resin ratio because the amount of resin applied is hard to control and manage.

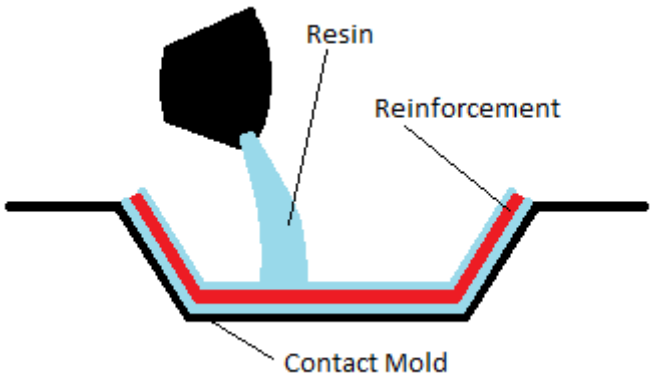
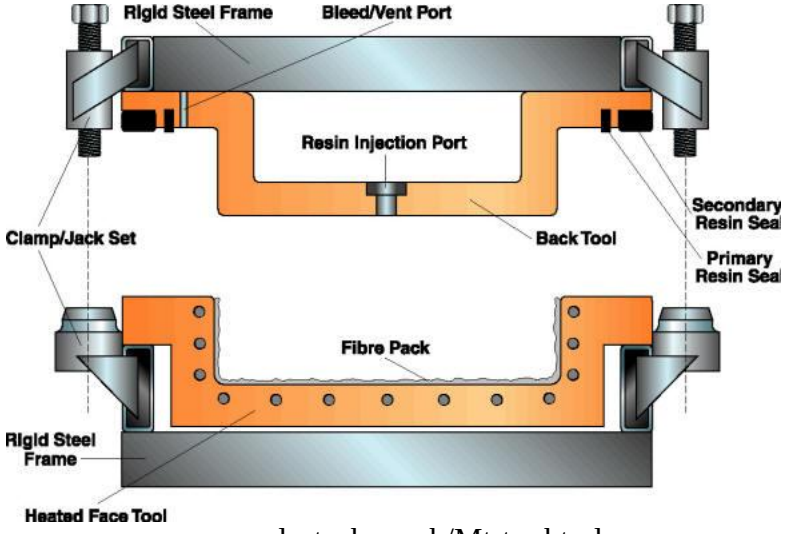


Figure 9 Hand lay-up diagram

1.7.2 Resin Transfer Molding

In resin transfer molding (Figure 10) the reinforcement material is contained in a dye. The matrix material, which is usually a thermoset polymer, is forced into the dye through channels precut into the dye cavity. In order for the matrix to flow through the channels properly the mold is kept at a temperature above the melting point of the polymer being used.

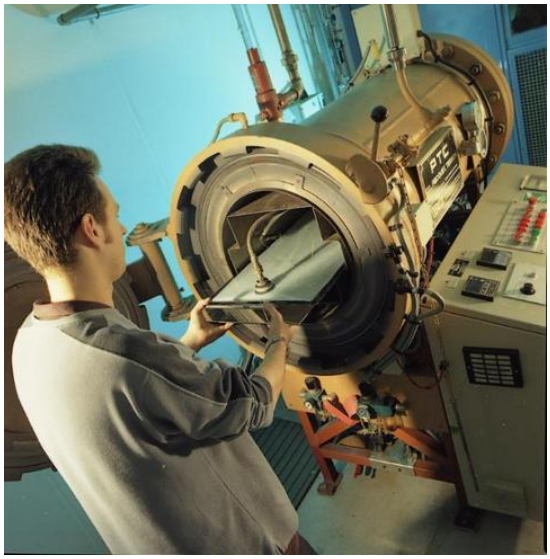


www.plastech.co.uk/Mtrtm.html

Figure 10 Resin transfer molding schematic

1.7.3 Autoclave

The autoclave first was used in medical applications to clean tools using a chamber that is pressurized using steam. The autoclave has since been adapted for composites molding. The composite part is sealed or bagged and placed in the autoclave chamber (Figure 11) then the steam is added. The heat from the steam helps speed up the curing process and the pressure during curing creates a greater laminate density for stronger structures.



www.npl.co.uk/autoclave-fabrication-of-compos...

Figure 11 Autoclaving

1.7.4 Vacuum Infusion

Vacuum Infusion was derived from a former process known as vacuum bagging. In vacuum bagging the fiber reinforcement and resin were sealed in a bag and then the excess resin is removed using a vacuum pump. In Vacuum Infusion the reinforcement is sealed in a bag (Figure 12) then using a similar vacuum pump at one end the resin is pulled through the reinforcement

from the other end. This process produces a composite with a very good fiber to resin ratio and has very minimal waste resin due to more manageable and controllable resin application.

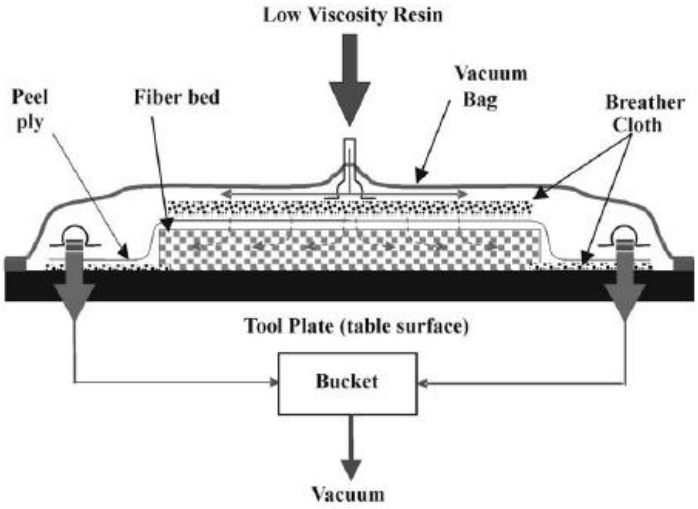


Figure 12 Vacuum infusion

1.8 Reinforcement Construction

In the attempt to further develop composites much development has taken place in the reinforcement structures (preforms) of these composites. There are many structures currently used within the composite world such as knitted, braided, non-woven, conventional woven and three dimensional woven structures. The majority of development is being done with the three-dimensional (3D) reinforcement structures because of improved properties of their two-dimensional (2D) counterparts. The following sections covered construction of woven preforms.

1.8.1 2D Structures

Two-dimensional fabrics were and are still used in some industries to this day. Composites would use multiple sheets of these fabrics to reinforce composites to attain strength properties needed depending on the end uses. 2D structures are based on conventional woven and non-woven fiber interaction. The 2D fabrics are produced using a mono-directional shedding (Figure 13) which means the fabric is formed using a single shed and a single x-direction insertion. One of the major drawbacks of the formation is the susceptibility to delamination. When producing composites using 2D fabrics multiple layers must be joined in order to obtain substantial thickness. When merging these layers there is a chance of air bubbles, moisture, and many other particulates to find their way into the structure which will cause voids within the composite. The inconsistencies of the structure caused by the voids will affect the properties of the composite as well as create areas where the structure can separate from itself (delamination).

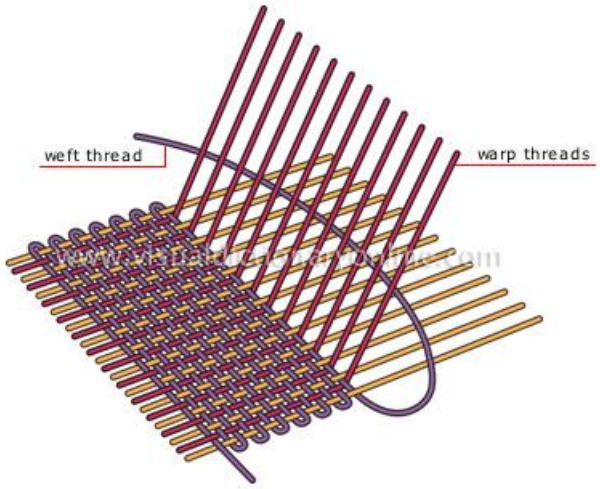


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Figure 13 2D woven fabric

1.8.2 3D Structures

As the field of composites grows the technology has expanded as well. Much of the early composites were 2D woven structure while currently 3D woven structures are being used in many composite applications. The increasing interest in composite structures from fibrous preforms inspired researchers to conduct intensive basic research which led to the establishment of a new generation of products and processes [18, 32, 33]. Among these is a novel process of manufacturing 3D woven fabrics, invented at the College of Textiles, North Carolina State University (NCSU) in the early 1990s [20]. The new technique outperforms the traditional 2D weaving technique that introduces crimp in the interlaced yarns, which causes negative impact on composite performance. The development of 3D reinforcement medium has been fueled by their ability to withstand multidirectional stress as well as eliminate delamination. Many different methods of weaving 3D structures have been developed, most being based on a

particular maximized property or specific end use. The basic technology is based on conventional weaving process but uses dual-directional shedding as opposed to mono-directional shedding of 2D weaving. The basic 3D weaving technologies use multilayer y-direction that add the thickness to the fabric. The multilayer y-direction of 3D weaving produces fabric on a volumetric basis, as seen in Figure 14, while 2D weaving produces fabric on an areal basis. Given certain weaving technologies woven preforms have been produced to near net shape as well as advancements in production of vascular prosthesis [34]. The 3D woven structure is achieved by simultaneous multiple filling insertions for each weaving cycle and does not involve the building up of single layers one layer at a time. Rather, an integrated single unit of thick fabric is formed from three orthogonal straight yarn systems (Figure 14). Figure 15 shows the invented 3D weaving machine for sample production for research and development. Large-scale machines were developed that enable weaving preforms of up to 2.5 cm thick and up to 280 cm wide from virtually any kind of fiber. This technology has been intensively commercialized aiming at developing applications for automotive, marine, personnel and vehicle armor, industrial, aerospace, wind energy generator, recreational, etc. [23].

The preforms made from this process show enhancement in mechanical properties compared to traditional thick preforms made from stacks of 2D woven or stitch-bonded fabrics. In general, these composites are characterized by: (1) High fiber volume fraction, (2) High strength to weight ratio, (3) Conform to desired complex shapes, (4) Excellent ability to transfer polymeric resin, (5) Hybridization of different fiber types in the weaving process, (6) Ability to produce complex shapes (I, T, J, box, truss, etc.), (7) Ability to control Z-fiber volume fraction from extremely low (1%) to extremely high levels (33%) to meet desired performance, (8) Not

susceptible to delaminating, and (9) Substantially improved damage tolerance, impact resistance and multi-hit ballistic protection capability.

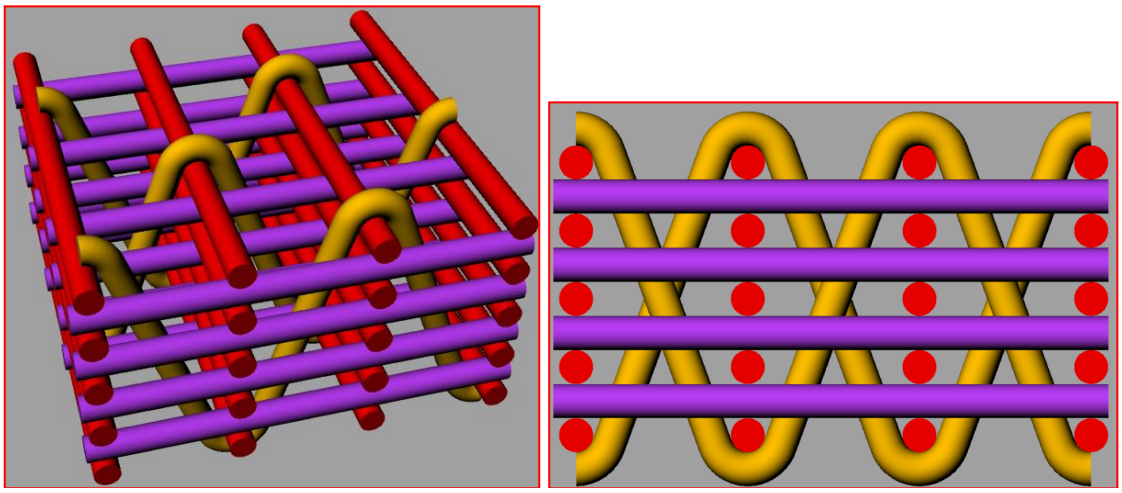


Figure 14 Schematic of thick, integral 3D woven structure

Figure 15 3D Weaving machine
top shows overall view of the 3D weaving machine and bottom shows the machine during multi-insertion of filling yarns (x-yarns) through multi-shed formed of y-direction yarns (y-yarns) and z-yarns (top and bottom sheets)

The two major classifications or definitions of 3D woven mediums are angle interlock and orthogonal interlock binding. From these definitions four different structures can be formed: shown in Figure 16.

- Angle interlock through the thickness (A/T)

- Angle interlock layer to layer (A/L)
- Orthogonal interlock through the thickness (O/T)
- Orthogonal interlock layer to layer (O/L)

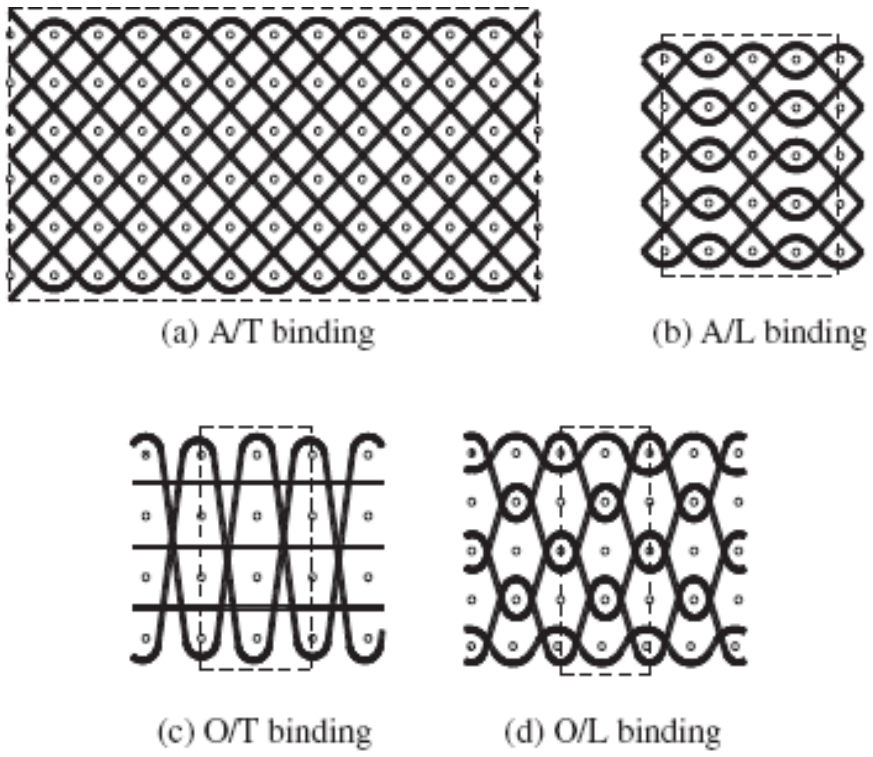


Figure 16 Three-dimensional woven structures with various binding patterns [35]

Orthogonal fabrics use what are called false sheds. A false shed is a shed or opening in the y-direction yarns that the x-direction yarn is inserted in but unlike conventional weaving this false shed does not close [3]. There is only one set of y-direction yarns that cross in this type of weaving. The set of y-direction yarns that cross are called Z yarns. These Z yarns pass through the false sheds and lock the x-direction yarns in place. Multiple false shed can be added for

increase thickness or formation of different structures. In Figure 17 you can see how the Z yarns (in red) are the only moving shed and lock the x-direction yarns (pink) in place.

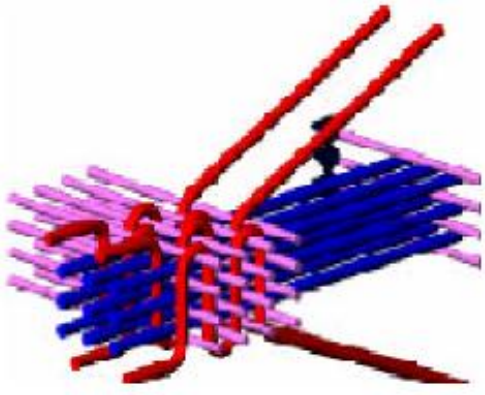


Figure 17 Non-interlaced 3D weaving [36]

Because of the versatility of the multiple sheds in 3D weaving, different structures can be woven. These structures are woven flat but are unfolded to create T structures, I structures, double crossed shapes, and many others depending on the weave design. These performs are usually woven using Prepreg fibers because of their complex shapes. It would be difficult to apply a resin after these structures are woven.

2. Objectives

The goal of this research is to construct a natural based composite structure using 3D woven cotton preforms consolidated with bio-based resin using the VARTM technology and evaluate their mechanical properties. To recent times natural composites have been formed using loose webs and some single layer fabrics (2D). These basic structures have provided insight into the possibility of high strength natural composites but do not provide the required properties to meet

market needs for high strength applications. Prior research in the area of fiberglass composites has led to believe that the 3D weaving technology provides a preform with better properties over conventional layering preform constructions [49].

Natural fibers provide a low weight high strength alternative because of their low cost as well as being environmentally friendly during processing and after its lifespan whether their recycling or put in landfills to deteriorate. Many natural fibers have been considered when approaching the natural fiber composite ideal such as Kenaf, Jute, and Hemp as well as others, but Cotton was chosen due to its availability as well as its ease of manufacture. In respect to most natural fibers with high strength properties cotton is found at the lower end. Although lower in strength and modulus than others, the possibilities for cotton are endless. There are many applications that currently are overwhelmed with the high strength properties of composites formed with high-performance fibers. There are potential markets that natural composites would meet property standards for numerous applications as well as be a lower cost alternative on top of the environmentally friendly aspect. Areas in the automotive industry have begun to adopt non-woven natural fiber based composites for applications requiring low strength properties such as trunk and roof liners [29,62]. With the push of the End of Life Vehicle (ELV) and Waste Electrical and Electronic Equipment Directive (WEEE) natural composites will move into applications such as body panels which require higher strength properties than nonwoven applications [23]. There are as well applications in the construction industry that would alleviate the over use of synthetic fibers. Composites are used in applications such as pre-manufactured tub and shower forms. Knowing that cotton has mechanical properties less than the previously stated fibers it allows for the natural composite to be studied and reformed to determine

properties controlled by structure and resin. This provides results for a base composite that can be improved using higher strength natural fibers to meet required mechanical properties in future product markets.

The resin chosen to be used with the cotton reinforcement is a bio-based epoxy resin. This resin uses a soy protein that reacts very similarly to epoxy groups. The resin contains 20% bio-content which allows the resin to maintain a high percentage of its mechanical properties in comparison to 100% epoxy, but improves the recyclability along with the environmental degradation of the resin. The resin was provided by Ashland Chemical. Ashland is currently researching and working on development of stable epoxy resins containing higher amounts of bio-content as well as resins that use recycled or reclaimed content. Although the resin is not 100% green it is a step in the right direction and is pushing other manufactures to move in the same direction.

The specific objectives to achieve the goal of the research work are:

1. Create functional composite panels from cotton 3D woven preforms and bio-based resin using VARTM.
2. Evaluate the panels to determine specific properties for tensile, flex and impact resistance.
3. Compare results of testing natural composites structures with fiberglass samples of similar construction and specifications.

3. Experimental Set-up

The basis of the experiment is to produce natural based preforms and infuse them with a natural based resin to produce bio-based composite structures. The succeeding sections discuss the materials, processes and testing used to produce and evaluate the properties of the bio-based composite panels.

3.1 Preform Materials

The composite preforms used in these trials were produced from 100% cotton yarns. The major impact on the selection of cotton is its ease of manufacture as well as its abundance. Additionally, it is one of the most green and environmentally friendly natural fibers. Cotton being one of the lesser of the natural fibers in terms of mechanical properties allows for future research into preform production using natural fiber with improved properties. By creating a base level natural composite further composite development can be tailored to industry specific applications by fiber choice. These natural composites would meet needs of applications such as pre-manufactured tub and shower units for the construction industry as well as body panel applications in the automotive industry.

The cotton fibers were ring spun to produce an average 6/1cc yarn from the manufacturer. The yarn produced was measured to find actual count and was found to have an average 5.92/1cc (99.7 tex). The single yarn had an average break force of 12.01 N and elongation at break of 6.37%. This was tested using the Uster Tensorapid 3 following ASTM test method D2256. In order to have sufficient yarn diameter to achieve reasonable composite thickness and fiber volume fraction, 5.92/1 yarns were plied using a 1959 model M Meadows ring twister. The y-

yarns were composed of 7 yarns plied to produce a 6/7 or 0.846 cc (698 tex; experimentally measured) yarn. The x- and z-yarns were composed of 3 yarns plied to produce 6/3 or 1.97 cc (300 tex; experimentally determined). The single yarn diameter was calculated using Pierce's method [70]. This method uses the following equation based on the yarn tex, packing factor of the yarn, and the fiber density to determine diameter of the yarn [73].

$$d(cm) = \frac{1}{280.2}\sqrt{\frac{N_t}{\phi \rho_f}}$$

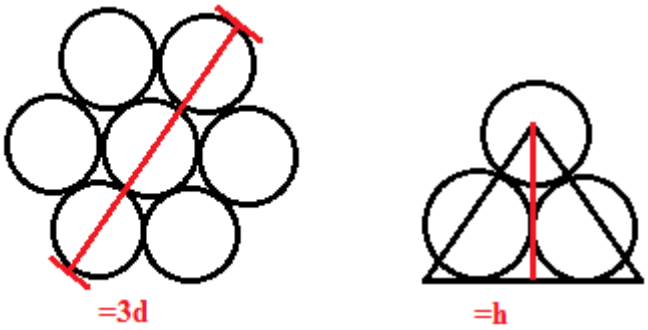
d= diameter of yarn (cm)

N_t = Yarn number (tex)

ϕ = Yarn packing factor

ρ_f = Fiber density

The average diameter of the single yarn (93 tex) was 0.0376 cm based on the equation and average packing factor of approximately 0.56 and fiber density of approximately 1.53. Given the diameter of the single strand the 7 and 3 ply yarns could be calculated based on the geometry of the yarns shown below.



The average diameter of the 7-ply yarns is based on three times the diameter of a single yarn shown by the geometry of 7-ply illustrated above. The diameter of these yarns is calculated to be 0.113 cm. Based on similar geometry shown for the 3-ply yarn the diameter is calculated to be approximately 0.0846cm. The size of the yarns was decided based on previous preform constructions using E-glass. Creating similar structures allowed the benchmarking of the natural composites to accepted mechanical properties of produced glass structures.

3.2 Construction of Composite Preform

The preforms were produced using 3D weaving technology donated by 3TEX, Inc. Two y-yarn arrangements were developed for the constructions of the preforms. The machine was set up with a width of 17 inch (43.18 cm) and drawn with one y-yarn per dent of the reed. The total dents were 102 giving 2.36 reed dents/cm. The total number of z-yarns used is 102 and the total y-yarns/layer is 102. In this research the number of y-yarn layers changed to produce composites of different constructions and study their influence on composites final properties. Two, three, and four y-yarn layers were used or total number of y-yarns of 204, 306, and 408 respectively.

Two weave structures were constructed; namely 2x2 warp rib and 2x2 basket. In 2x2 warp rib, the y-yarn : z-yarn sequence (or arrangement) per layer is 1:1. For example a single dent for the three layer construction would have one z-yarn and 3 y-yarns (1 for each layer). The y- and z-yarns were drawn alternating creating the 1y:1z yarns/layer sequence to create the proper interlacement. This creates a z-yarn interlacement on either side of every y-yarn, which in turn locks the x-yarns in place shown in Figure 14.

The second construction, which is 2x2 basket, was created by using a 2 y-yarns/layer followed by 2 z-yarns. This structure was selected under the preconception of less interlacement (less x-yarns in this case) creating a looser fabric. This understanding is based on prior knowledge of conventional woven structures. Seen in Figure 18 the arrangement is 1:1 having interlacements on either side of every y-yarn in a layer. The yarn structure is also observed in the surface view as well as the cross-sectional view (Figure 19). Each yarn within the complete plied structure is visible. The yarn passing through in the z-direction can also been seen in Figure 19.

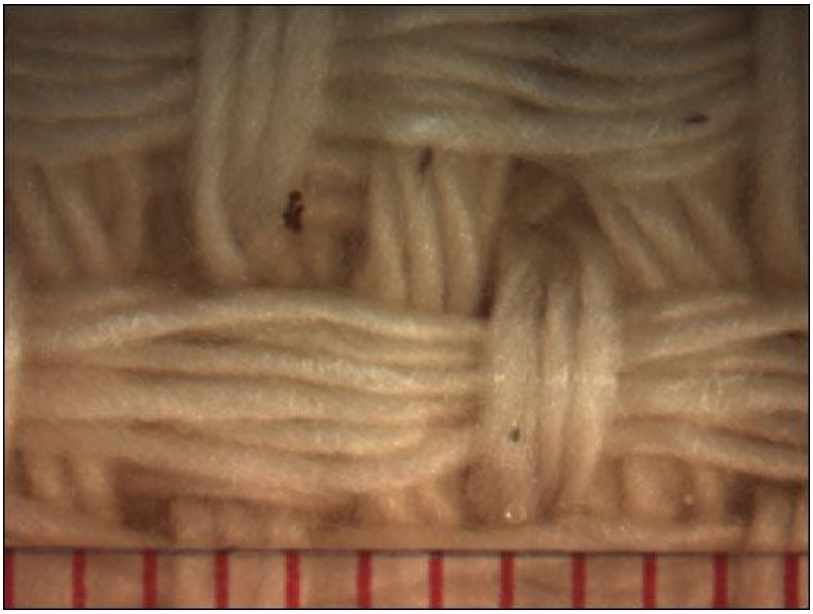


Figure 18 1:1Arrangement of woven composite preform surface (top view)

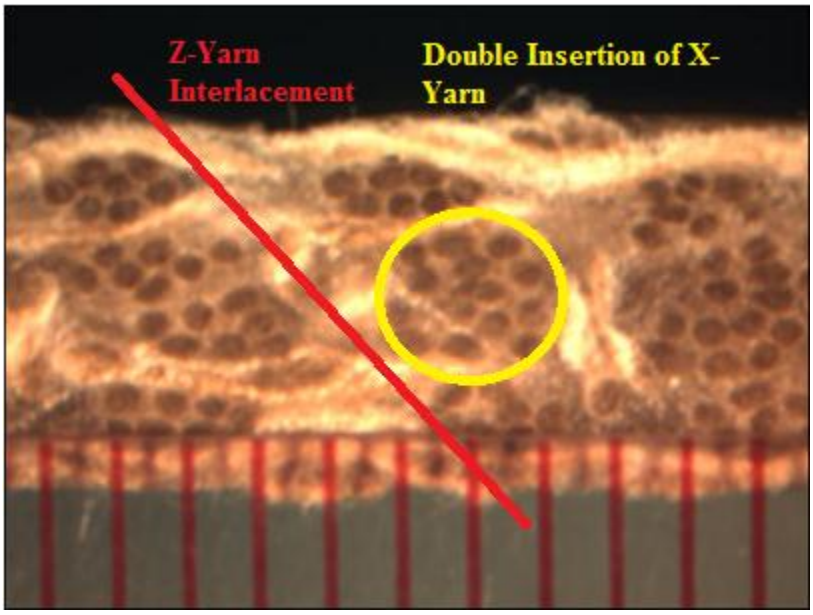


Figure 19 1:1 Arrangement woven composite preform cross-section

3.3 Consolidation of Composites

The 3D woven cotton preforms were consolidated using the Vacuum Assisted Resin Transfer Molding. Vacuum assisted resin transfer molding (VARTM) is a relatively recent development of the resin transfer molding (RTM) methods and has been increasingly used for consolidation of fiber reinforced composite preforms. It was developed to reduce manufacturing costs and enhance performance of composites by speeding up the process of resin infusion through preforms and to obtain composite structures with no or minimum voids in order to avoid flaws and premature failure. Composites made by VARTM method have better quality and mechanical properties compared to those of RTM composites as well as lower tooling costs [15, 16]. The VARTM process is especially effective for large area moldings. As mentioned earlier, none of the published work on composites from natural materials took advantage of VARTM method. VacMobiles® 20/2 VARTM equipment, which is available at the NCSU College of Textiles, was used for resin infusion.

The preforms of dimension of 43.18 cm x 43.18 cm each with orientation of the sample length (y-direction) in the direction of the resin flow (to observe the effect of varying the x-yarn density since number of y-yarns/layer did not change) were prepared with one layer of release film underneath the preform followed by one layer of peel ply on top of the preform and flow media was applied on top of the peel ply to provided improved flow properties. These layers were then sealed using industrial double sided tape under a final layer of infusion bagging plastic. This sequence seen in Figure 20 is tested by putting the preform under vacuum and checked for leaks using an Amprobe TMULD-300 ultra-sonic leak detector before being exposed to resin. In the last photo of Figure 20 the resin flow front is shown moving across the preform. The curvature of

the resin flow front is created because of the central location of the vacuum port which creates a more directed vacuum in the center of the set-up.

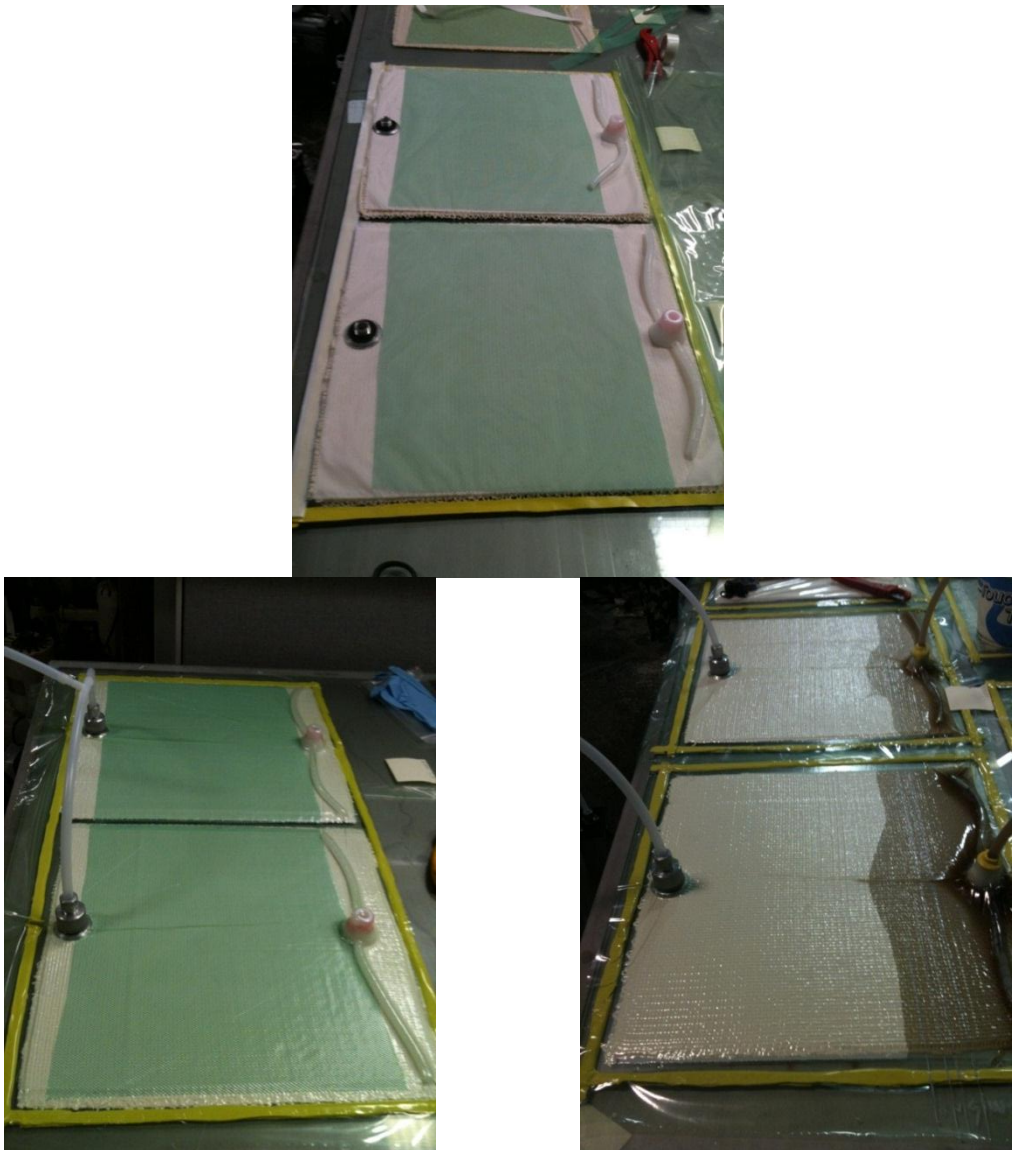


Figure 20 Vacuum infusion set-up and sequence

3.4 Composite Testing and Evaluation

For all standardized measurements and property testing ASTM and ISO test methods were followed to provide reliable data for analysis. The standards used for each test are equivalent to methods followed for the testing of similar constructed composites using fiberglass. By using the same methods across both fiber types, the end composite properties can be compared and be used for benchmarking in the current and future research. The composites were characterized by construction, thickness, and fiber volume fraction (FVF). The constructions were grouped by number of y-direction layers (y-yarns), y- to z-yarn arrangement, and x-yarn density. Three different levels of number of layers were used to obtain different preform thicknesses; 2 layer, 3 layer, or 4 layer. The x-yarn density was also varied for each preform enable the evaluation of property change within each layer grouping. Four x-yarn densities were calculated based on balancing the yarn weight for the x-direction and y-direction. The x-yarn densities were calculated (see Appendix A) based on using the rule that the total denier of y-yarns/unit width (measured along x-axis) equals the total denier of x-yarns/unit length (measured along y-axis). By balancing the densities in both directions the structure should provide directional unbiased testing results. Unbalanced x- and y-yarns were also considered in the main experiment. The balanced structures were used as control for each variation in layers to base tested properties on.

3.5 Test Methods

The following test methods were observed during the testing of the composites produced. Each test method was followed to ensure repeatability for further testing and comparison.

3.5.1 ASTM D4762-11- Testing Polymer Matrix Composite Materials

The initial standard that was used to determine the tests to follow for the evaluation was ASTM D4762-11. This standard breaks down each mechanical property of polymer composites and has testing methods to be followed based on fiber type or general composite formation. This was used as a basic guide to elect the tests that best fit the information needed for successful testing of the natural composites.

3.5.2 ASTM 1777- Thickness of Textile Materials

This test method applies to the testing of fabrics including but not limited to coated woven fabrics. The composite specimens are placed on the base of a caliper and the presser foot is closed on the specimen oriented in the thickness dimension. The displacement between the base and presser foot is measured to give the thickness of the composite. The thickness is measured in multiple points along the length of the sample and an average thickness is calculated based on the measurements taken. Thickness is one of the basic physical properties of textile materials and is an important factor in determining many other normalized mechanical properties since thickness affects the cross-section area of tested samples. This method was used to measure thickness of each specimen before each mechanical test.

3.5.3 ASTM D3039- Tensile Properties of Polymer Matrix Composite Materials

The in-plane tensile properties of the composites were measured following the standard ASTM 3039. The samples were cut using a CAD rotary cutting device, available at PPG of Shelby, NC, to eliminate variation in the testing samples. Properties, in the test direction, which may be

obtained from this test method include the following: Ultimate tensile Strength, Ultimate tensile strain, and Tensile chord modulus of elasticity, Poisson's ratio, and Transition strain.

3.5.4 ASTM D790 - Flexural Properties

This test method is used to determine the flexural properties of reinforced plastics that include composite structure. The test uses a three-point loading apparatus (three-point bending) with two outer structures supporting the specimen from underneath at a determined span with a load added from above at the center of the span. Flexural properties vary with specimen thickness so the span can be moved to compensate for thickness to provide specific properties for varying thicknesses.

3.5.5 ISO 7765- Dynatup Drop Weight -Determination of Puncture Impact Behavior

The Dynatup is used for high velocity drop weight testing. This test method determines the puncture impact behavior of the specimens. It provides data to show properties of impact energy, which is a measure of impact resistance of the material, to achieve breaking load as well as the deflection at break load.

3.5.6 ASTM D5961 Bearing Response

This test method covers the bearing response of pinned or fastened joints using multi-directional polymer matrix composite laminates reinforced by fibers single-shear tensile or compressive loading of a two-piece specimen. The samples were prepared with a width of 1.5 in and length of 5.5 in. For each test two samples were required. The two samples are overlapped at the point of

pinning. The effective overlap is 1.5 in giving a test gage length of 7in. During testing the sample strength was observed as well as the mode of failure.

4. Comparison between Bio Resin and Epoxy Resin

Two resin types were investigated to understand their benefit in relation to flow properties, thickness, and strength properties. A 100% epoxy resin and an epoxy resin with 20% bio-content were tested to determine the effect of the bio-content on the final composites' performance. The resins were added to preforms constructed using cotton yarns produced through 3D weaving as it was described earlier. Experiments were performed to compare the flow properties and post infusion thickness of epoxy resin and bio-based resin in 3D woven cotton preforms.

Three preform constructions were produced and were infused using two different matrix materials (Table 6). In total 6 composites were developed. Table 7 shows the details of the parameters of the 6 composite panels produced along with their thickness and weight results. The x-yarn densities were calculated based on a y-yarn : z-yarn of 1:1 arrangement (2x2 warp rib weave) fabric construction and the yarn diameters to produce a balanced preform. The preforms were woven on the 3D weaving machine donated by 3TEX, Inc. The samples were then infused using a Vacmobiles™ 20/2 infusion vacuum (VARTM). Both the Derakane and Envirez resins were prepared using 1% initiator per volume. The initiator used was a 45% concentration of MEKP due to its temperature stability for storage. Laboratory conditions during infusion were 20ºC and 49% humidity giving an approximate gel time of 40 minutes based on estimations

provided by the resin supplier. The samples were infused at 690 kilopascal (100 psi) vacuum pressure for 60 minutes then inlet and outlet were sealed and the samples were kept under vacuum for an additional 120 minutes to accommodate for complete curing. It should be mentioned here that the improved (adding mesh transfer media) method of resin infusion to reduce resin flow time was not practiced in this experiment.

Table 6 Resin trail design

Parameter	Levels
Preform Layers and x-yarn density (threads/cm/layer)	4y/5x, 4.46 3y/4x, 4.14 2y/3x, 3.68
Resin	Derakane 8084 (Epoxy) Envirez 86400 INF (Bio)

Table 7 Sample construction and physical properties

Sample ID	# of Layers (y/x)	x-yarn Density (threads/cm/layer)	Resin Type	Thickness (mm)	Weight of Composite (g/cm^2)
1	2/3	3.68	Epoxy	2.6	0.274
2	3/4	4.14	Epoxy	3.5	0.374
3	4/5	4.46	Epoxy	4.6	0.478
4	2/3	3.68	Bio	2.5	0.334
5	3/4	4.14	Bio	3.4	0.418
6	4/5	4.46	Bio	4.3	0.528

The fixed parameters for this experimental design were:

Linear Density of x-yarns: 300 (g/km or tex)
Linear Density of y- yarn: 698 (g/km or tex)
Linear Density of z-yarns: 300 (g/km or tex)
y-yarn : z-yarn arrangement: 1:1 (2x2 warp rib weave)

The textile preforms as well as finished composite panels were tested to gather data for detailed evaluation. The structures were measured for thickness according to ASTM D1777 and the weight of each dry preform was also taken. Measurements were taken before and after infusion to determine added thickness due to infusion. The flow properties of the two resins were also observed. Measurements were taken every 3, 7, 10, 15, 20, 25, and 30 minutes to reveal the relationship between the resin flow front and preform construction parameters and resin type. Using the preform structures as the control this allowed for the resin types to be compared based on viscosity.

The fiber volume fraction was calculated for each sample. Using the following equation the FVF was calculated using the results from the weight measurements and resin and fiber densities.

$$V_f = \frac{\rho_m W_f}{\rho_f W_m + \rho_m W_f}$$

V_f = volume fraction of fibers

W_f = weight of fibers

W_m = weight of matrix

ρ_f = density of fibers

ρ_m = density of matrix

The tensile strength of the samples was also investigated. Each sample was prepared according to ASTM 3039. The samples were tested following ASTM D3039 for composite tensile

properties using the MTS Mini Bionix hydraulic tensile test system. The bolt bearing properties of the composites were also tested using ASTM D5961. These tests allowed for comparison of the epoxy and bio resins in terms of their effect on the tensile and bolt bearing strength.

The fiber volume fraction for each sample was calculated based on the previous equation and the provided density measurements found in Tables 8 and 9.

The results of Table 10 show that the Epoxy samples resulted in a lower FVF compared to bio-based samples. This can be attributed to the slower flow front (Figure 22) resulting in resin build-up within the sample. The thickness results of Figure 21 support this finding. Higher Epoxy composite thickness indicates more resin in the sample compared to bio-based resin composites. The difference in flow distance between the samples is shown in Figure 22 and it is apparent that the Epoxy resin was unable to pass with ease through the preforms compared to the bio-based resin. This can be attributed to the high viscosity of the Epoxy resin compared to the bio-based resin.

Table 8 Resin properties

Resin Type	**Resin Density (g/cm^3)**	**Resin Viscosity (mPa-s)**	**Tensile Strength (mPa)**	**Tensile Modulus (GPa)**	**Elongation at Break (%)**
Epoxy	1.14	360	76.00	2.90	10.0%
Bio-based	1.11	150	70.32	3.17	3.9%

Table 9 Fiber and resin weights

Sample ID	Weight of Preform (g/cm^2)	Weight of Composite (g/cm^2)	Weight of Resin (g/cm^2)
1	0.096	0.274	0.179
2	0.127	0.374	0.246
3	0.173	0.478	0.305
4	0.095	0.334	0.240
5	0.127	0.418	0.291
6	0.173	0.528	0.356

Figure 21 shows the results of the thickness of each sample as affected by resin type and number of y-yarn layers. The 4-layer preforms have the highest thickness due to more y-yarn and x-yarn layers in their construction. The 4-layer preform infused using Derakane epoxy resin showed a higher resulting composite thickness than the composites infused using Envirez bio-based resin. This can be attributed to the difference in viscosity between the two resins shown in Table 8. The high viscosity of the epoxy resin decreased the ability to flow causing a buildup over the effective resin absorption area. Also in the infusion set-up the resin first has to disperse through the thickness of the preform then across creating an increasing back pressure as more resin is introduced. In comparing the thickness to the resin flow front seen in Figures 21 and 22 one can see a vast difference in thickness and flow properties of the epoxy and bio-based resins.

Table 10 Fiber volume fraction

Sample ID	Fiber Volume Fraction (%)
1	24.0
2	24.0
3	24.8
4	24.6
5	25.0
6	26.5

In Table 11 and Figures 23-26, the data shows the difference in tensile and bolt bearing breaking strength which can be attributed to the decreased strength of the bio-based resin itself. Although the break strength shows little noticeable difference between resin types, the modulus of the bio-based resin proved to be at least 50% higher than that of the epoxy resin due to the higher modulus of the bio resin compared to Epoxy resin and the lower thickness of the composites from bio resin compared to the thickness of composites from Epoxy resin.

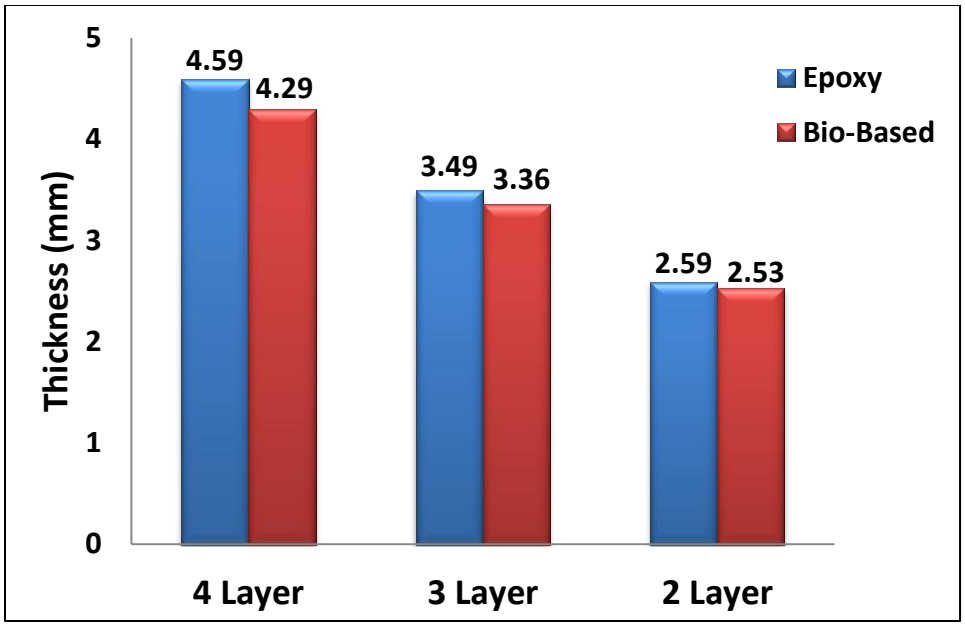


Figure 21 Epoxy and bio-based composite thickness

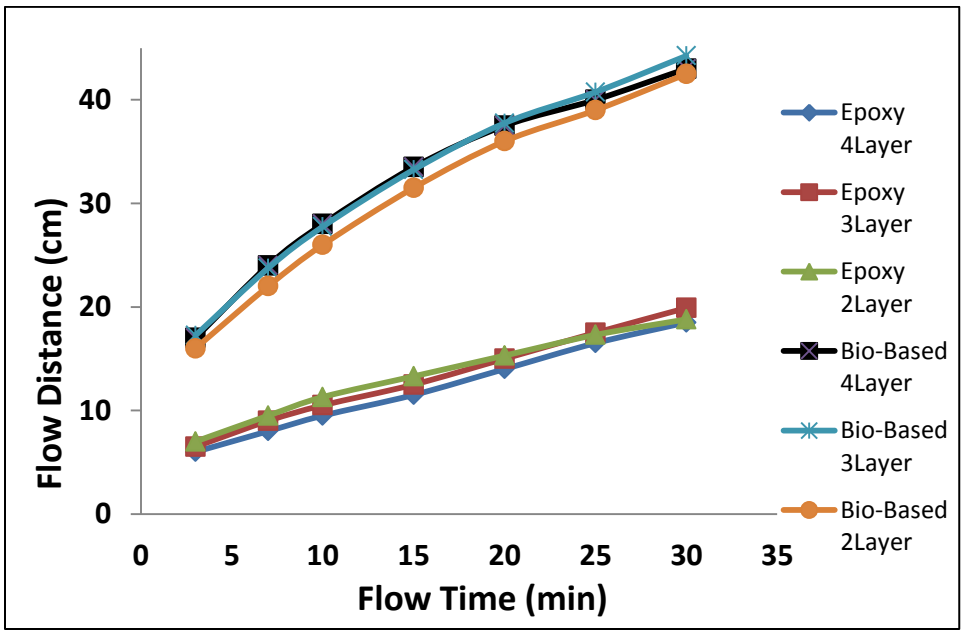


Figure 22 Epoxy and bio-based resin flow front

Table 11 Peak Tensile Properties

Composite ID	Peak Load (N)	Peak Stress (Mpa)	Strain at Peak Load (%)	Modulus (Mpa)
4Layer Epoxy	5923	50.8	9.74	5.2
3Layer Epoxy	4726	53.3	7.91	6.7
2Layer Epoxy	3079	46.8	6.36	7.4
4Layer Bio-based	5077	46.6	5.73	8.1
3Layer Bio-based	3791	44.4	5.72	7.8
2Layer Bio-based	2589	40.3	3.73	10.8

Table 12 Peak Bolt Bearing Tensile Properties

Composite ID	Peak Load (N)	Peak Stress (Mpa)	Strain at Peak Load (%)	Modulus (Mpa)
4Layer Epoxy	2796	15.9	4.55	2.7
3Layer Epoxy	2627	19.7	4.56	3.6
2Layer Epoxy	2942	29.8	4.83	6.0
4Layer Bio-based	3620	22.1	3.91	4.7
3Layer Bio-based	2854	22.2	3.38	5.8
2Layer Bio-based	2523	26.1	4.35	5.9

As seen in Figures 23 and 25 the peak load has an average decrease of approximately 50% for both the 3 and 4 layer composite constructions while the 2 layer share very similar break strengths for tensile and bolt bearing test of 2589N and 2523N respectively. The peak stress was also investigated and in Figure 24 a consistent stress is seen throughout the different layer constructions in the tensile testing. The bolt bearing tensile results did not share the same

consistency which can be seen in Figure 26 where the peak stress actually decreased with an increase in number of layers.

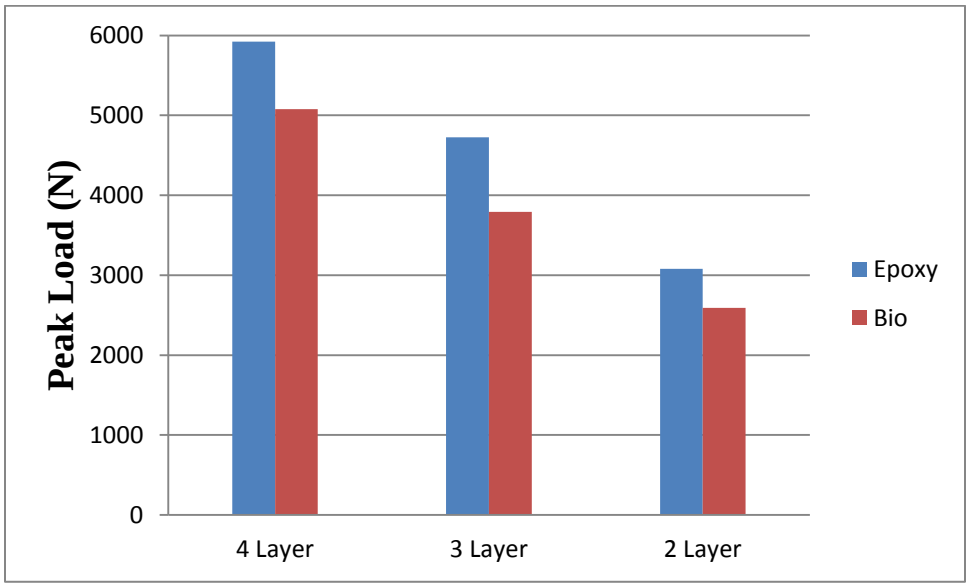


Figure 23 Tensile peak load comparison of epoxy and bio resin composites

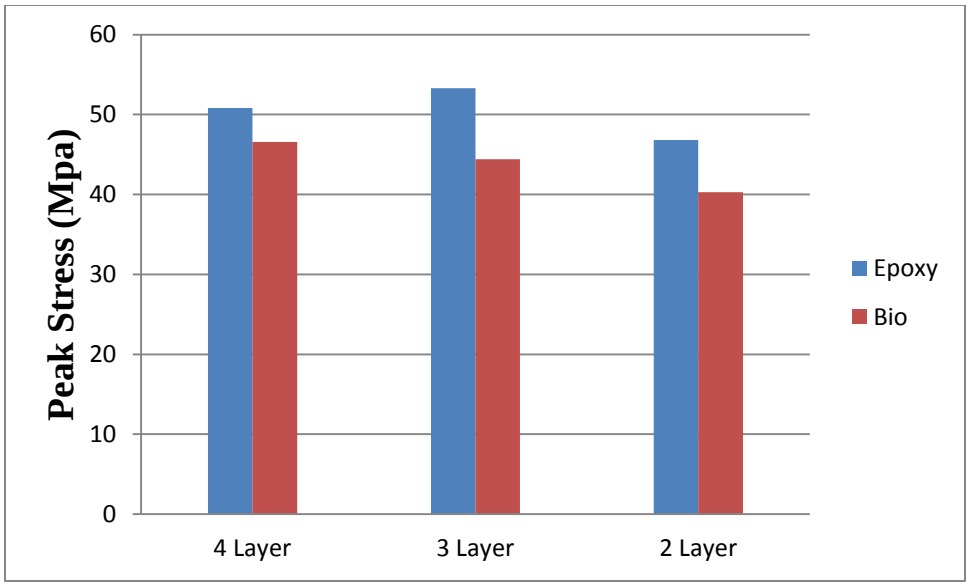


Figure 24 Tensile peak stress comparison of epoxy and bio resin composites

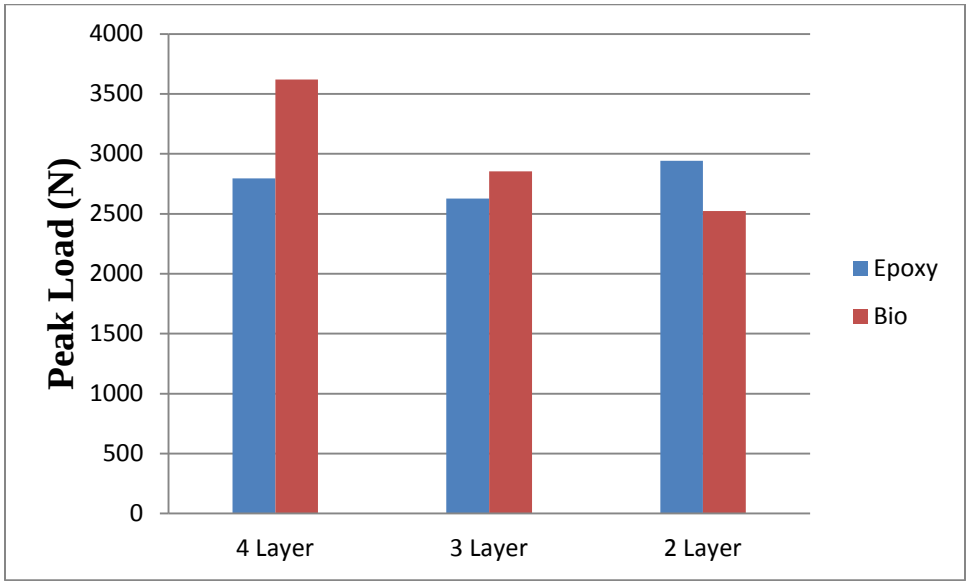


Figure 25 Bolt bearing peak load comparison of epoxy and bio resin composites

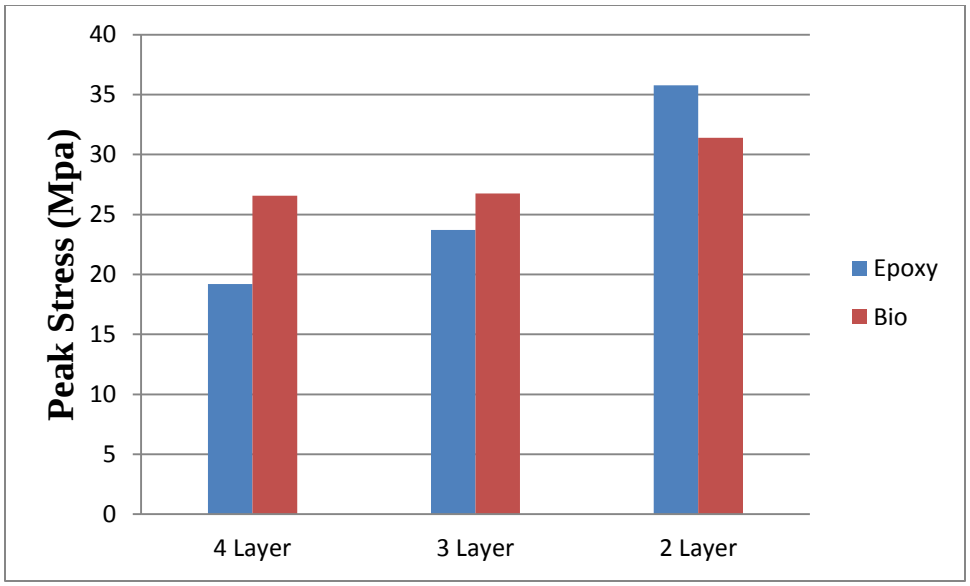


Figure 26 Bolt bearing peak stress comparison of epoxy and bio resin composites

Composite panels were successfully produced using 3D weaving technology and vacuum infusion method for both epoxy and bio-based resins. The influence of resin viscosity and preform thickness were studied to show interaction with flow front and composite thickness. From the weight and thickness measurements the Fiber Volume Fraction was calculated and each resin type was compared to show a slightly higher % fiber for the bio-based resin samples. The results from the flow and thickness measurement also show that viscosity significantly affects the flow properties and directly impacts the overall thickness of the composite panels. The higher panel thickness of the composites from Epoxy resin is caused by the build-up of resin given an increased amount of resin than the bio-based panels. From this experiment, it is concluded that bio-base resin exhibited higher flow rates and lower thickness with low loss in strength compared to the Epoxy resin samples.

5. Main Experimental Design: Cotton/Bio-Resin Composites

The main goal of this research is to produce composite from natural materials and test and evaluate them to determine their performance characteristics and identify end uses based on their performance. This section deals with experimental design devoted to produce composites from 100% cotton preforms and infuse them with bio-based resign described earlier. Similar processing (as described earlier) was used to create 24 panels with constructions seen in Tables 13 and 14. Samples 1, 6, 11, 13, 18, and 23 of Table 14 (in bold text) are balanced structures.

Table 13 Composite Experimental Design

Parameter	**Levels**
Preform Layers	4y/5x 3y/4x 2y/3x
x-yarn Density, threads/cm/layer	4.92 4.46 4.14 3.68
y-yarn : z-yarn arrangement	1:1 2:2

Table 14 Cotton/Bio Sample Construction and physical properties

Sample ID	Arrangement (y-yarn : z-yarn)	# of Layers (y/x)	x-yarn density (threads/cm/layer)	Thickness (mm)	Preform Weight (g/cm^2)	Weight (g/cm^2)	Fiber Volume Fraction
1	**1:1**	**2/3**	**3.68**	**3.20**		**0.32**	**22.2**
2	1:1	2/3	4.14	3.25		0.33	22.2
3	1:1	2/3	4.46	3.33		0.33	22.2
4	1:1	2/3	4.92	3.53		0.34	22.2
5	1:1	3/4	3.68	2.74		0.40	23.9
6	**1:1**	**3/4**	**4.14**	**2.69**		**0.42**	**23.9**
7	1:1	3/4	4.46	2.54		0.42	23.9
8	1:1	3/4	4.92	2.72		0.41	23.9
9	1:1	4/5	3.68	4.17		0.53	26.0
10	1:1	4/5	4.14	4.17		0.52	26.0
11	**1:1**	**4/5**	**4.46**	**4.29**		**0.51**	**26.0**
12	1:1	4/5	4.92	4.09		0.52	26.0
13	**2:2**	**2/3**	**3.68**	2.34		**0.29**	**22.2**
14	2:2	2/3	4.14	2.39		0.28	22.2
15	2:2	2/3	4.46	2.67		0.28	22.2
16	2:2	2/3	4.92	2.92		0.29	22.2
17	2:2	3/4	3.68	3.81		0.37	23.9
18	**2:2**	**3/4**	**4.14**	3.99		**0.39**	**23.9**
19	2:2	3/4	4.46	3.94		0.38	23.9
20	2:2	3/4	4.92	4.01		0.38	23.9
21	2:2	4/5	3.68	3.43		0.49	26.0
22	2:2	4/5	4.14	3.12		0.50	26.0
23	**2:2**	**4/5**	**4.46**	3.48		**0.48**	**26.0**
24	2:2	4/5	4.92	3.51		0.47	26.0

The fixed parameters used for this experimental design are:

Linear Density x-yarns: 300 (g/km or tex)
Linear Density y- yarn: 698 (g/km or tex)
Linear Density z-yarns: 300 (g/km or tex)
Resin: Envirez 86400 INF (bio-based resin)

The resin was added to preforms constructed using cotton yarns produced through 3D weaving. Tests were performed to show properties of strength, flex, and impact resistance of the composite panels. The preforms were woven on the 3D weaving machine donated by 3TEX, Inc. The

samples were then infused using a Vacmobiles™ 20/2 infusion vacuum (VARTM). The Envirez resin was prepared using 1% initiator per volume. The initiator used was a 45% concentration of MEKP due to its temperature stability for storage. Laboratory conditions during infusion were 20ºC and 49% humidity giving an approximate gel time of 40 minutes based on estimations provided by supplier. The samples were infused at 690 kilopascal (100 psi) vacuum pressure for 60 minutes then inlet and outlet were sealed and the samples were kept under vacuum for an additional 120 minutes to accommodate for complete cure time.

6. Results and Discussion

This section discusses the results gathers from the mechanical test methods used in evaluating the natural composite panels.

6.1 3D woven Preform Characterization

The 3D woven fabrics were produced using the 3D Weaving machine to create the preform reinforcement component of the composite structure. The cotton preforms were varied by number of layers and x-yarn densities to determine their effect on the composite. Because of this the composites were categorized by their construction and mechanical properties. With the exception of impact resistance, the mechanical properties were tested in both the y- and x-directions to determine if a directional bias is present in the construction of the preforms. The thickness of the composite was also taken into consideration to normalize the strength of the composites in terms of stress properties.

Figure 27 shows a noticeable trend in increasing thickness of the composite with the increase of number of layers. With the increase in x-yarn density per layer grouping the thickness of the composite showed an increase as well. With some variation the basic trend shows that the 2:2 arrangement structures have higher average thickness than the 1:1 arrangement structure. The 1:1 arrangement structure did show higher uniformity in thickness related through increase x-yarn density and through the increased number of y-yarn layers. As expected, the number of layers and thickness are directly related.

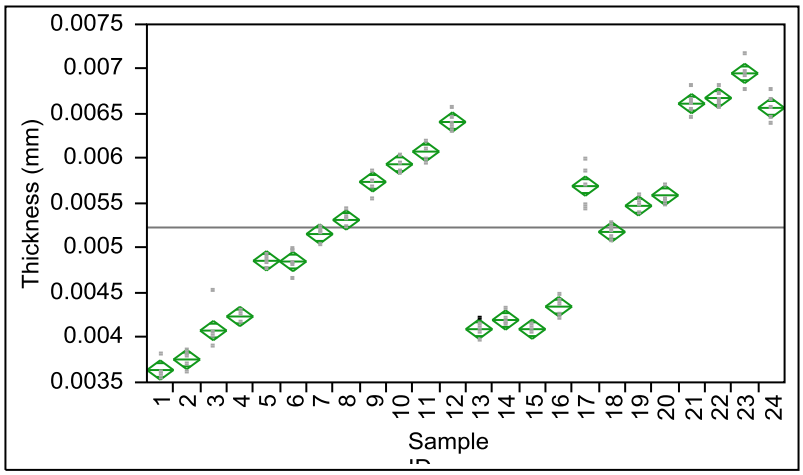


Figure 27 Thickness in terms of composite constructions
(ID representing the preform construction is explained in Table 11)

Although the samples measured for thickness were within the statistically accepted level of variation there was still variation within each preform construction. Each sample was measured in five locations to determine an average thickness. There is variation noticed between the five measurements taken of the composite samples independent of the number of layers and x-yarn

densities. This proves that the composites to be tested have a non-uniform thickness and will show effects in the mechanical properties in testing. The uniformity is affected by the placement of the inlets and outlets during infusion. The areas closer to the resin inlet showed higher thickness due to the build-up of resin at these points.

6.2 Tensile Properties

In textile manufacturing it is known that orientation is a key factor in mechanical properties and tensile strength being at the top of those properties. The direction with higher alignment has improved tensile properties. Within the preform structures there are two major in-plane directions of alignment, the x-direction and the y-direction. The tensile properties of both were taken into consideration during testing. The general trend that can be seen in Tables 15 and 16 is the increase of the Max Load as the number of layers and x-yarn density are increased.

Table 15 Tensile Properties in x-direction

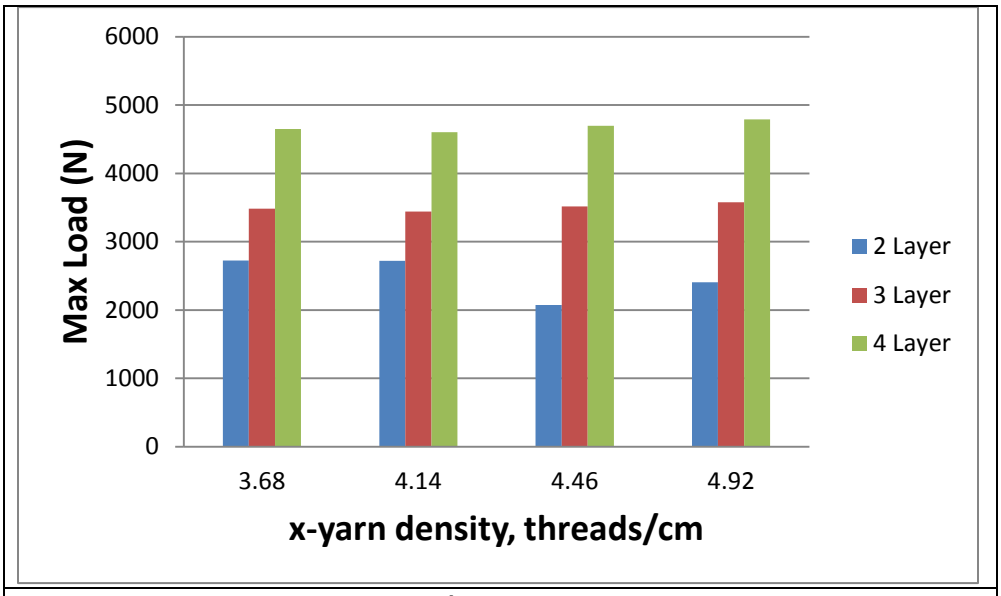
Sample ID	Arrangement (y-yarn : z-yarn)	# of Layers (y/x)	x-yarn density (threads/ cm/layer)	Thickness (mm)	Width (mm)	Max Load (N)	Max Load (kN)	Max stress (Mpa)	Tensile strain at max load (%)
1	**1:1**	**2/3**	**3.68**	**2.36**	**25.4**	**2,562**	**2.56**	**42.8**	**7.24**
2	1:1	2/3	4.14	2.46	25.4	2,786	2.79	44.3	6.57
3	1:1	2/3	4.46	2.69	25.4	2,899	2.90	42.6	6.67
4	1:1	2/3	4.92	2.87	25.4	2,750	2.75	37.9	7.08
5	1:1	3/4	3.68	3.07	25.4	2,988	2.99	38.1	6.46
6	**1:1**	**3/4**	**4.14**	**3.15**	**25.4**	**3,880**	**3.88**	**48.4**	**7.32**
7	1:1	3/4	4.46	3.28	25.4	3,409	3.41	40.9	6.05
8	1:1	3/4	4.92	3.51	25.4	3,705	3.71	41.5	6.24
9	1:1	4/5	3.68	3.66	25.4	4,314	4.31	46.3	8.21
10	1:1	4/5	4.14	3.86	25.4	3,450	3.45	35.1	7.53
11	**1:1**	**4/5**	**4.46**	**3.99**	**25.4**	**4,269**	**4.27**	**42.3**	**8.24**
12	1:1	4/5	4.92	4.29	25.4	4,310	4.31	39.6	8.18
13	**2:2**	**2/3**	**3.68**	**2.67**	**25.4**	**2,069**	**2.07**	**30.5**	**4.58**
14	2:2	2/3	4.14	2.64	25.4	2,254	2.25	33.5	4.48
15	2:2	2/3	4.46	2.59	25.4	1,869	1.87	28.5	5.55
16	2:2	2/3	4.92	2.84	25.4	2,475	2.47	34.3	5.82
17	2:2	3/4	3.68	3.78	25.4	1,955	1.95	20.3	6.48
18	**2:2**	**3/4**	**4.14**	**3.30**	**25.4**	**2,927**	**2.93**	**35.0**	**5.74**
19	2:2	3/4	4.46	3.40	25.4	3,247	3.25	37.5	6.30
20	2:2	3/4	4.92	3.58	25.4	3,224	3.22	35.5	5.83
21	2:2	4/5	3.68	4.17	25.4	4,064	4.06	38.4	7.71
22	2:2	4/5	4.14	4.22	25.4	3,702	3.70	34.6	7.78
23	**2:2**	**4/5**	**4.46**	**4.39**	**25.4**	**3,783**	**3.78**	**34.0**	**7.11**
24	2:2	4/5	4.92	4.09	25.4	3,808	3.81	36.7	7.13

Table 16 Tensile Properties in y-direction

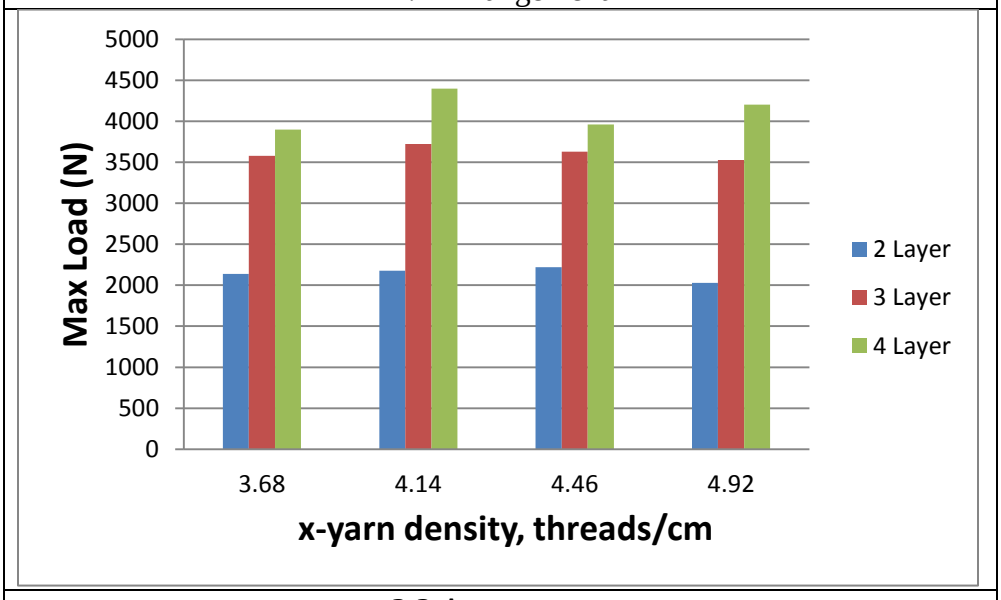
Sample ID	Arrangement (y-yarn : z-yarn)	# of Layers (y/x)	x-yarn density (threads/cm /layer)	Thickness (mm)	Width (mm)	Max Load (N)	Max Load (kN)	Max Stress (Mpa)	Tensile strain at Maximum Load (%)
1	**1:1**	**2/3**	**3.68**	**3.20**	**25.4**	**3,485**	**3.48**	**42.9**	**7.30**
2	1:1	2/3	4.14	3.25	25.4	3,440	3.44	41.7	6.82
3	1:1	2/3	4.46	3.33	25.4	3,516	3.52	41.6	7.00
4	1:1	2/3	4.92	3.53	25.4	3,578	3.58	39.9	7.55
5	1:1	3/4	3.68	2.74	25.4	2,724	2.72	39.4	6.05
6	**1:1**	**3/4**	**4.14**	**2.69**	**25.4**	**2,718**	**2.72**	**39.8**	**6.19**
7	1:1	3/4	4.46	2.54	25.4	2,073	2.07	32.3	7.09
8	1:1	3/4	4.92	2.72	25.4	2,407	2.41	34.8	6.03
9	1:1	4/5	3.68	4.17	25.4	4,649	4.65	44.0	7.59
10	1:1	4/5	4.14	4.17	25.4	4,604	4.60	43.6	7.93
11	**1:1**	**4/5**	**4.46**	**4.29**	**25.4**	**4,697**	**4.70**	**43.2**	**7.21**
12	1:1	4/5	4.92	4.09	25.4	4,788	4.79	46.1	7.48
13	**2:2**	**2/3**	**3.68**	**2.34**	**25.4**	**2,138**	**2.14**	**36.1**	**6.88**
14	2:2	2/3	4.14	2.39	25.4	2,175	2.18	35.9	6.01
15	2:2	2/3	4.46	2.67	25.4	2,219	2.22	32.9	5.60
16	2:2	2/3	4.92	2.92	25.4	2,027	2.03	27.4	6.38
17	2:2	3/4	3.68	3.81	25.4	3,896	3.90	40.4	7.49
18	**2:2**	**3/4**	**4.14**	**3.99**	**25.4**	**4,399**	**4.40**	**43.4**	**7.96**
19	2:2	3/4	4.46	3.94	25.4	3,960	3.96	39.7	8.56
20	2:2	3/4	4.92	4.01	25.4	4,201	4.20	41.3	9.06
21	2:2	4/5	3.68	3.43	25.4	3,576	3.58	41.0	6.69
22	2:2	4/5	4.14	3.12	25.4	3,721	3.72	46.8	7.70
23	**2:2**	**4/5**	**4.46**	**3.48**	**25.4**	**3,629**	**3.63**	**41.1**	**6.76**
24	2:2	4/5	4.92	3.51	25.4	3,529	3.53	39.5	6.90

The samples in bold in the above table are samples specifically designed to have equal weight of the x- and y-yarns to provide balanced properties that theoretically should have no or little directional bias in terms of mechanical properties. Most of the samples tested showed higher mechanical properties in the y-direction than in the x-direction especially when comparing the peak stress values. Since the thickness varied within each composite panel, the stress was calculated for each of the 5 specimens was calculated (Tables B.1and B.2 of Appendix B show the results of the individual observations of tensile tests.

In Figures 28 and 29 a comparison can be seen between the x- and y-directions that tensile strength is proven to be better in the y-direction. The number of layers in sample configuration shows a dominating effect on the tensile properties of the composites.



1:1 Arrangement



2:2 Arrangement

Figure 28 Max tensile load in terms of composite construction in y-direction

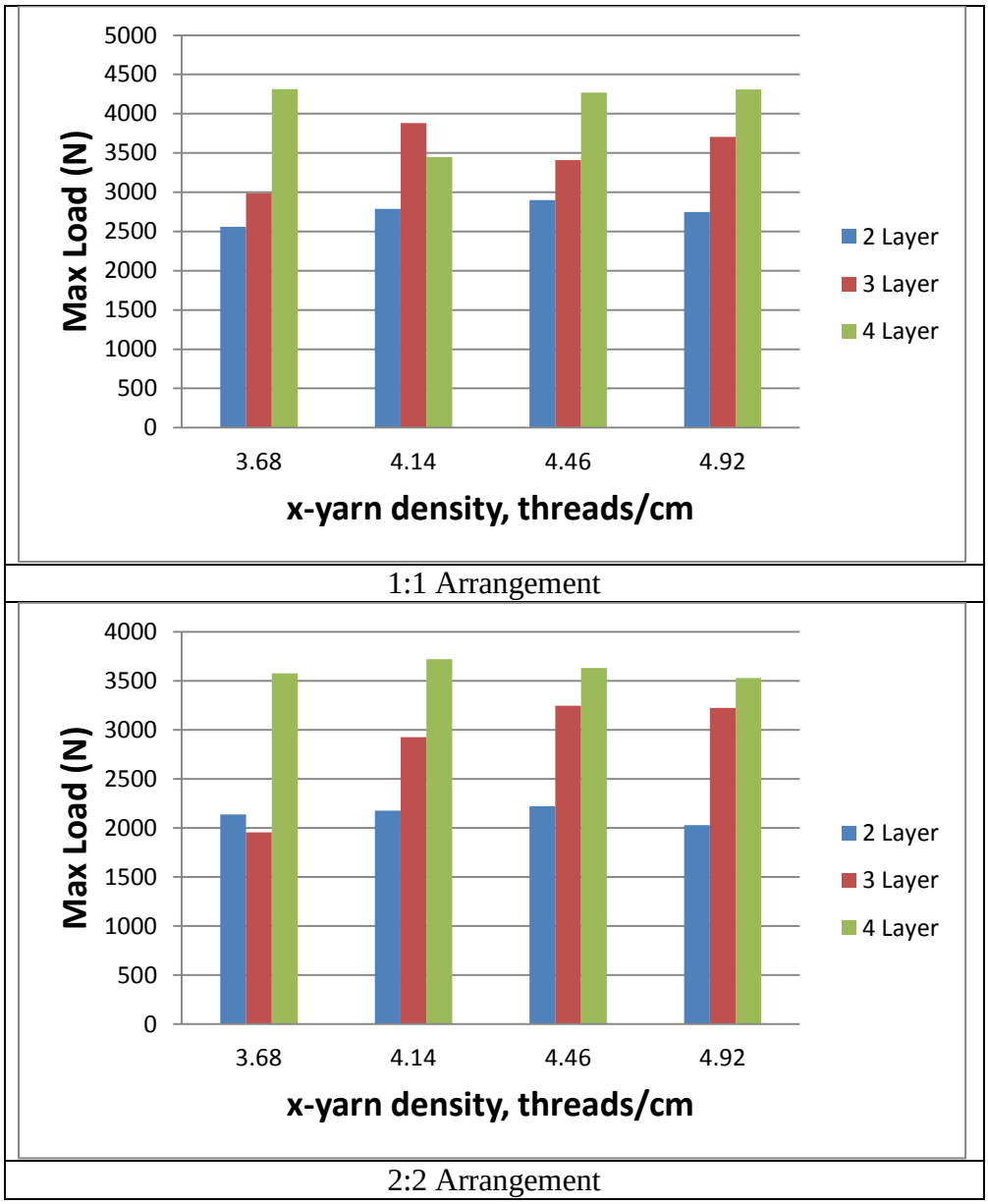
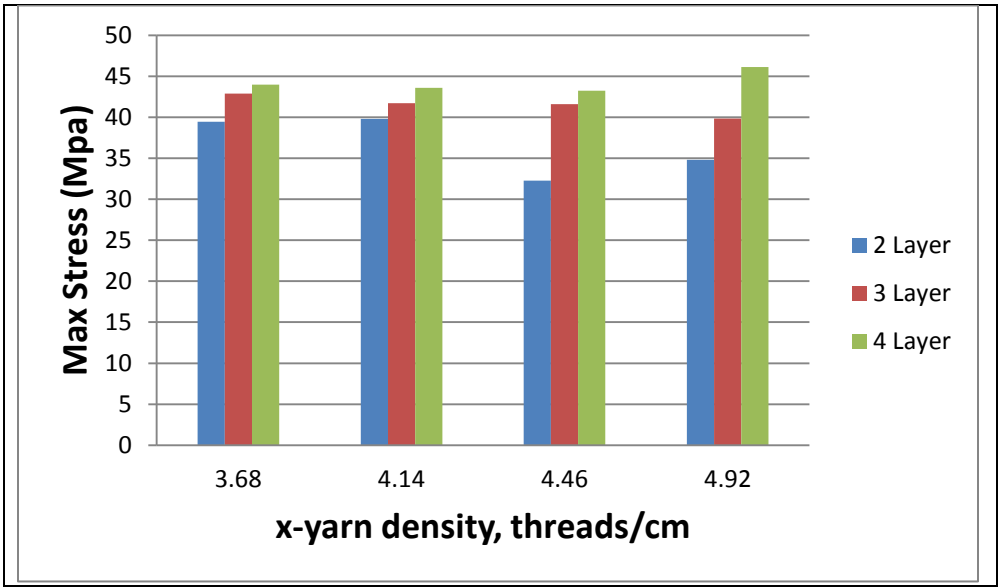


Figure 29 Max tensile load (N) in terms of construction in x-direction

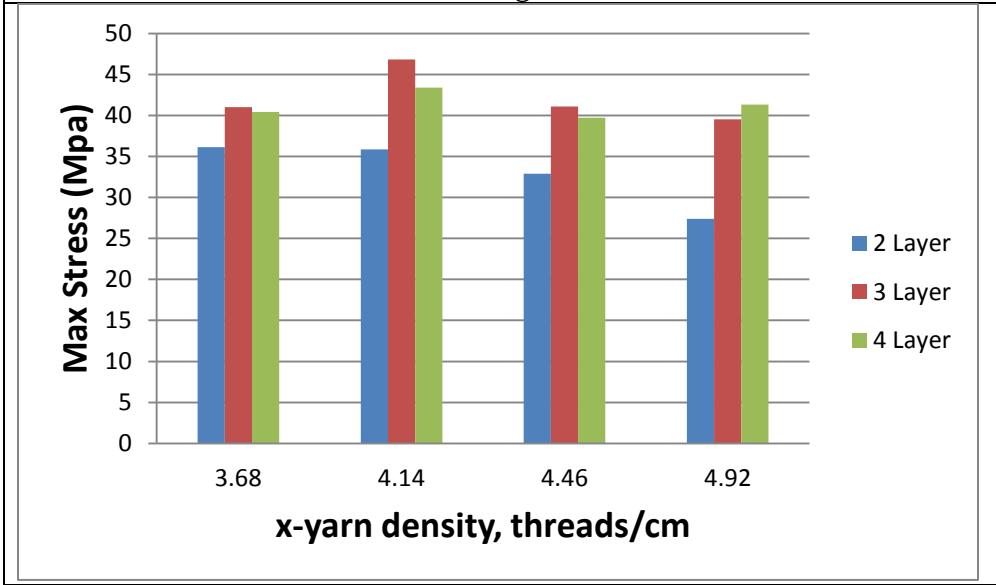
On average the 1:1 arranged structure had a higher Peak Load which can be attributed to the thicker preforms shown previously in Tables 15 and 16. Most of the 1:1 arrangement structures

show higher peak load and peak stress in x- and y-directions over the 2:2 arrangement as shown in Figures 29, 30 and 31. The testing in the x-direction shows more consistent results than the results for the y-direction.

The means were compared to determine any differences among the stress values and it is shown that results for both x-direction and y-direction have a similar overall mean stress, but among each layer group there is little variation to prove difference.



1:1 Arrangement



2:2 Arrangement

Figure 30 Analysis of max tensile stress (Mpa) in y-direction

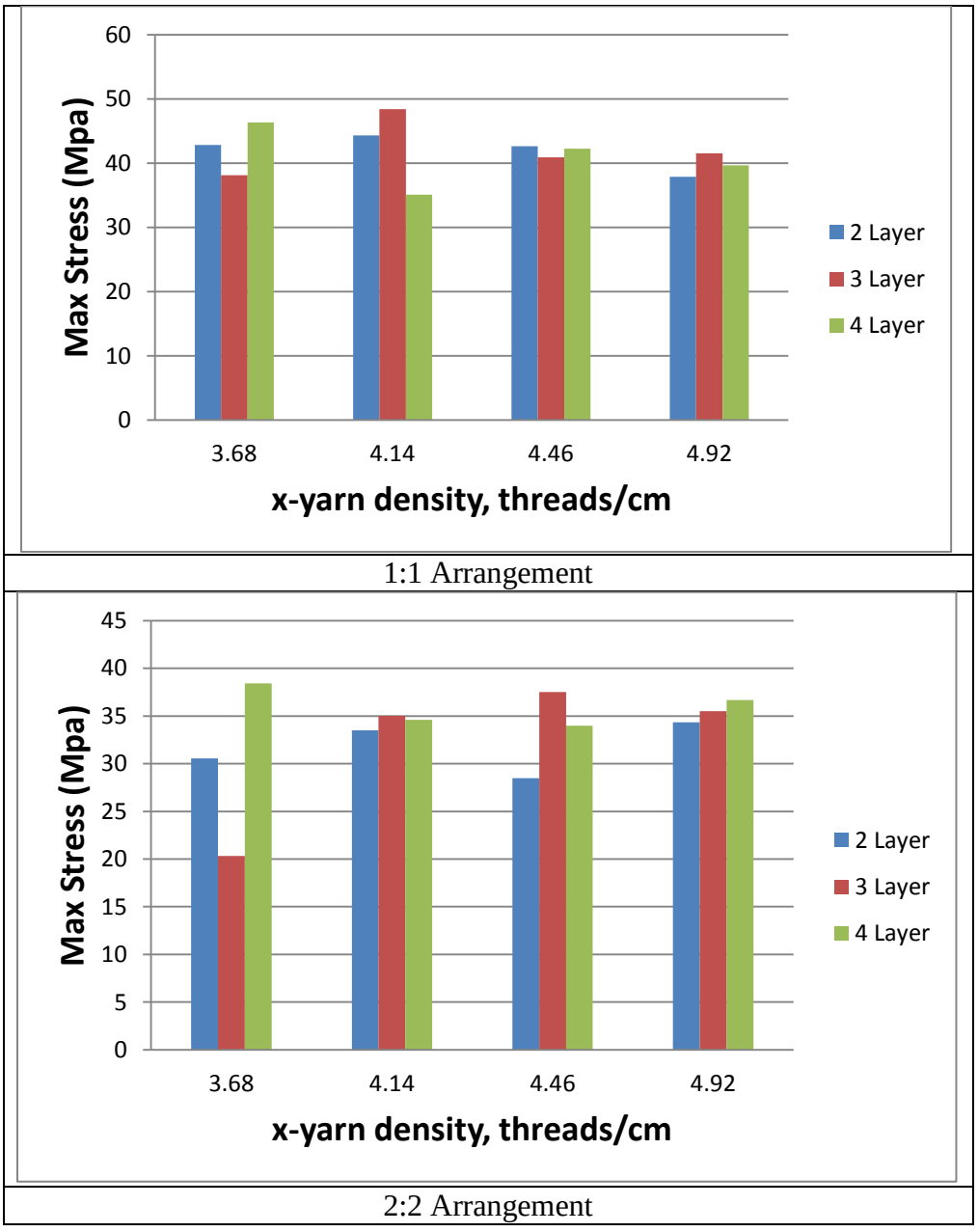


Figure 31 Analysis of max tensile stress (Mpa) in x-direction

Figures 32 and 33 show the graphic presentation of the strain results of the 24 composite structures in terms of x-yarn density, number of layers and y:z yarn arrangement.

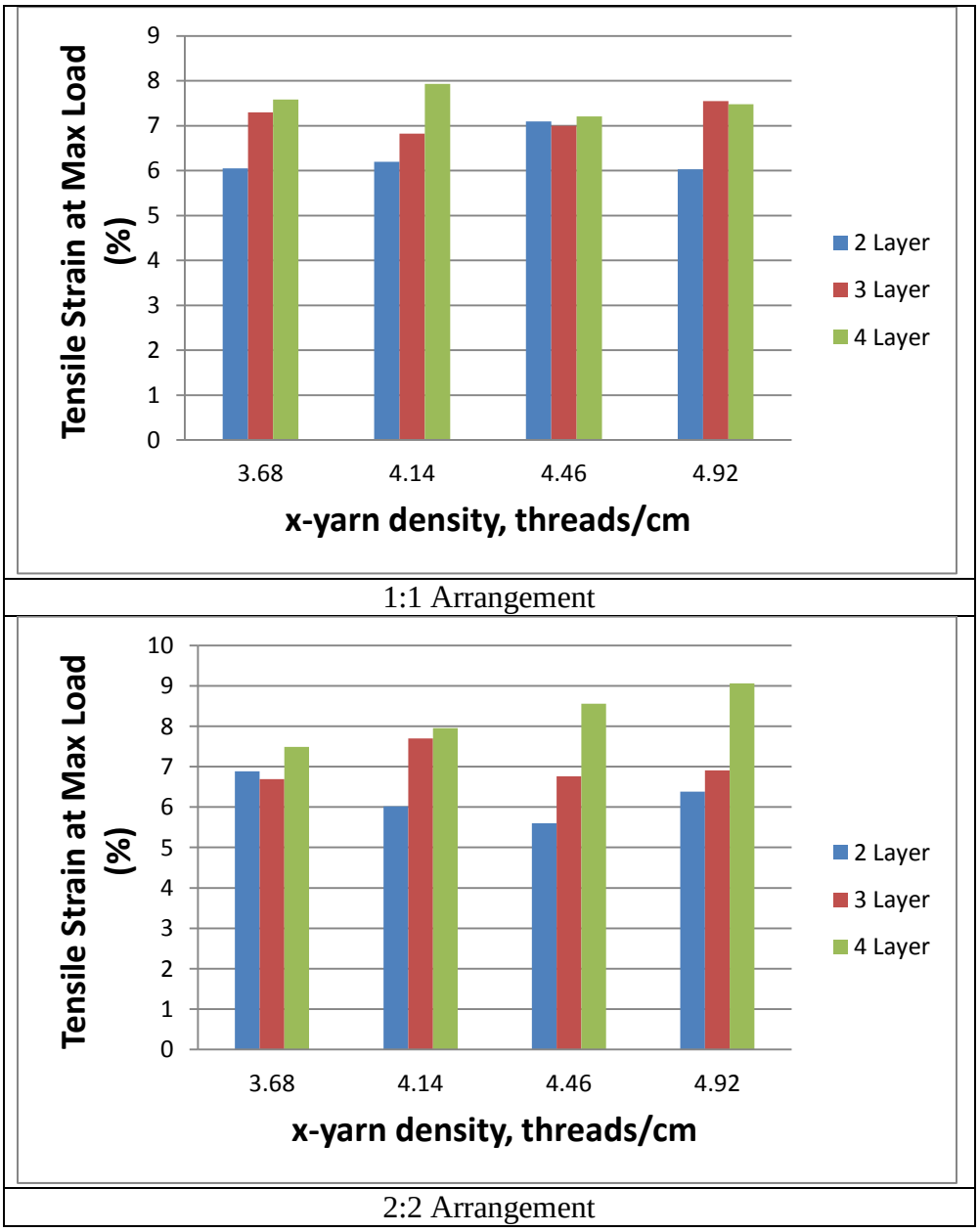
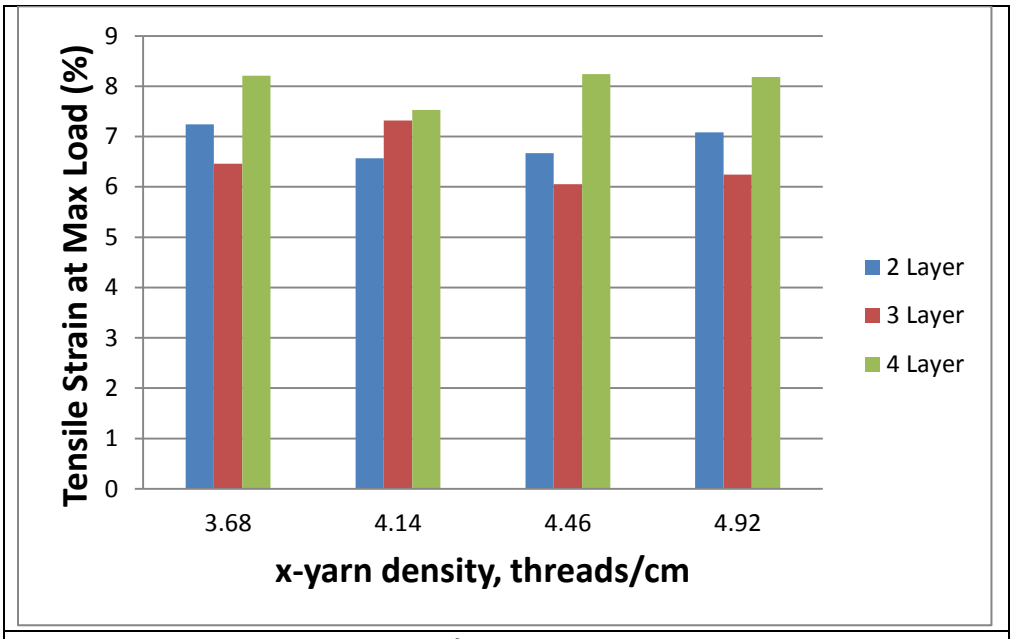
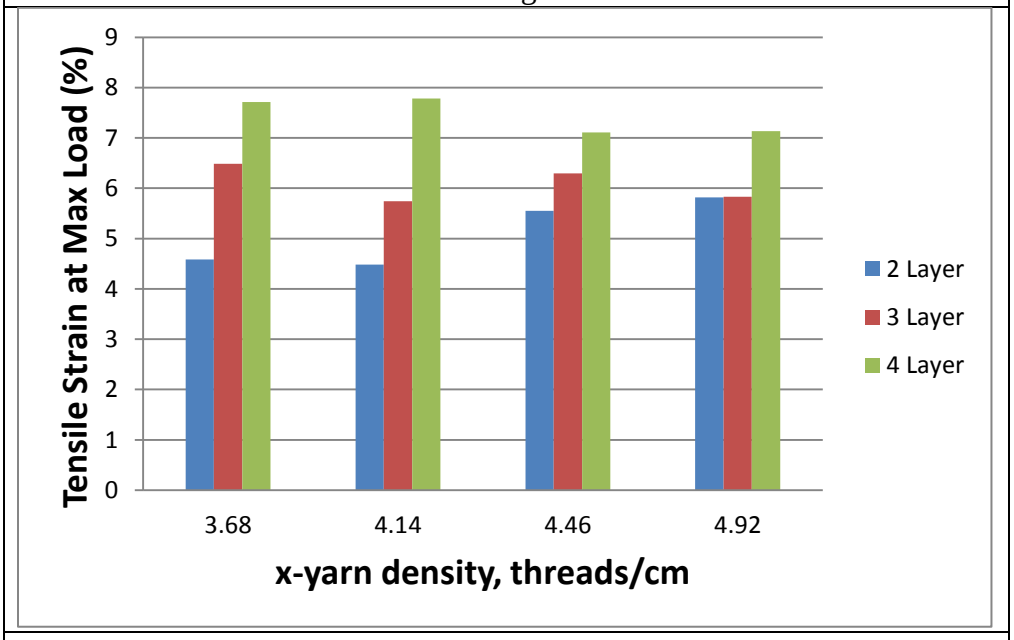


Figure 32 Analysis of tensile strain at Maximum Load (%) y-direction



1:1 Arrangement



2:2 Arrangement

Figure 33 Analysis of tensile strain at maximum load (%) in x-direction

6.3 Flex Properties

Tables 17 and 18 show the results of the 3-point flexural test of the 24 composites. In analyzing the results from flexural testing of the specimens it was observed that within each grouping of layer number there is slight variation in the flexural properties. Although noticeable increase in strength shown in Figure 34 based on the testing or comparison of means there was generally only differences seen between the samples of two and three layers. The importance of this increase in thickness is the determination of the testing span shown in Figure 35.

Table 17 Flexural Properties with x-direction orientation

Sample ID	Arrangement (y-yarn : z-yarn)	# of Layers (y/x)	x-yarn density (threads/cm/layer)	Width (mm)	Depth (mm)	Span (mm)	Max Load (N)	Max flex stress (Mpa)	Young's Modulus (Automatic Limit) (Mpsi)
1	**1:1**	**2/3**	**3.68**	**25.7**	**2.36**	**37.6**	**212**	**84.5**	**0.476**
2	1:1	2/3	4.14	25.6	2.41	38.6	236	91.5	0.531
3	1:1	2/3	4.46	25.5	2.62	41.9	220	78.3	0.475
4	1:1	2/3	4.92	25.4	2.74	43.7	236	80.5	0.508
5	1:1	3/4	3.68	25.6	3.12	49.8	258	77.8	0.505
6	**1:1**	**3/4**	**4.14**	**25.7**	**3.18**	**50.8**	**304**	**89.9**	**0.519**
7	1:1	3/4	4.46	25.6	3.30	52.8	287	81.7	0.502
8	1:1	3/4	4.92	25.6	3.71	59.4	270	68.3	0.425
9	1:1	4/5	3.68	25.6	3.71	59.4	276	69.5	0.438
10	1:1	4/5	4.14	25.7	3.86	61.7	293	70.9	0.453
11	**1:1**	**4/5**	**4.46**	**25.6**	**4.06**	**65.0**	**272**	**63.0**	**0.426**
12	1:1	4/5	4.92	25.8	4.14	66.0	224	50.8	0.442
13	**2:2**	**2/3**	**3.68**	**25.5**	**2.59**	**41.4**	**190**	**69.0**	**0.429**
14	2:2	2/3	4.14	25.7	2.64	42.4	216	76.1	0.511
15	2:2	2/3	4.46	25.7	2.59	41.4	151	54.6	0.371
16	2:2	2/3	4.92	25.7	2.84	45.5	179	59.1	0.496
17	2:2	3/4	3.68	25.7	3.61	57.7	182	48.0	0.359
18	**2:2**	**3/4**	**4.14**	**25.8**	**3.20**	**51.1**	**286**	**83.8**	**0.581**
19	2:2	3/4	4.46	25.6	3.43	54.9	314	86.1	0.550
20	2:2	3/4	4.92	25.8	3.61	57.7	294	76.5	0.583
21	2:2	4/5	3.68	25.8	4.29	68.8	302	66.0	0.522
22	2:2	4/5	4.14	25.8	4.27	68.3	325	71.4	0.514
23	**2:2**	**4/5**	**4.46**	**25.7**	**4.37**	**69.6**	**365**	**78.3**	**0.523**
24	2:2	4/5	4.92	25.7	4.11	65.8	332	75.7	0.496

Table 18 Flexural Properties with y-direction Orientation

Sample ID	Arrangement (y-yarn : z-yarn)	# of Layers (y/x)	x-yarn density (threads/cm/layer)	Width (mm)	Depth (mm)	Span (mm)	Max Load (N)	Max flex stress (Mpa)	Young's Modulus (Automatic Limit) (Mpsi)
1	**1:1**	**2/3**	**3.68**	**25.7**	**2.34**	**37.5**	**195**	**77.6**	**0.518**
2	1:1	2/3	4.14	25.6	2.41	38.6	195	75.6	0.548
3	1:1	2/3	4.46	25.5	2.64	42.1	185	67.1	0.543
4	1:1	2/3	4.92	25.4	6.30	43.6	165	25.0	0.483
5	1:1	3/4	3.68	25.6	3.12	50.0	317	94.7	0.785
6	**1:1**	**3/4**	**4.14**	**25.7**	**3.12**	**50.0**	**282**	**84.4**	**0.575**
7	1:1	3/4	4.46	25.6	3.33	53.0	265	75.0	0.548
8	1:1	3/4	4.92	25.6	3.43	54.8	246	67.3	0.490
9	1:1	4/5	3.68	25.6	3.71	59.1	320	81.4	0.514
10	1:1	4/5	4.14	25.7	3.84	61.2	236	57.5	0.420
11	**1:1**	**4/5**	**4.46**	**25.6**	**3.91**	**62.7**	**239**	**57.0**	**0.441**
12	1:1	4/5	4.92	25.8	4.14	66.2	261	58.6	0.427
13	**2:2**	**2/3**	**3.68**	**25.5**	**3.35**	**54.1**	**191**	**61.6**	**0.506**
14	2:2	2/3	4.14	25.7	2.72	43.4	209	72.2	0.491
15	2:2	2/3	4.46	25.7	2.64	42.1	177	62.7	0.409
16	2:2	2/3	4.92	25.7	2.79	44.9	218	73.0	0.480
17	2:2	3/4	3.68	25.7	3.68	58.6	245	63.6	0.406
18	**2:2**	**3/4**	**4.14**	**25.8**	**3.33**	**53.3**	**254**	**70.8**	**0.494**
19	2:2	3/4	4.46	25.6	3.53	56.3	252	66.9	0.441
20	2:2	3/4	4.92	25.8	3.61	57.6	286	74.1	0.548
21	2:2	4/5	3.68	25.8	4.27	68.3	327	71.7	0.533
22	2:2	4/5	4.14	25.8	4.32	68.8	351	76.0	0.553
23	**2:2**	**4/5**	**4.46**	**25.7**	**4.47**	**71.6**	**353**	**73.3**	**0.511**
24	2:2	4/5	4.92	25.7	4.24	67.8	334	73.6	0.470

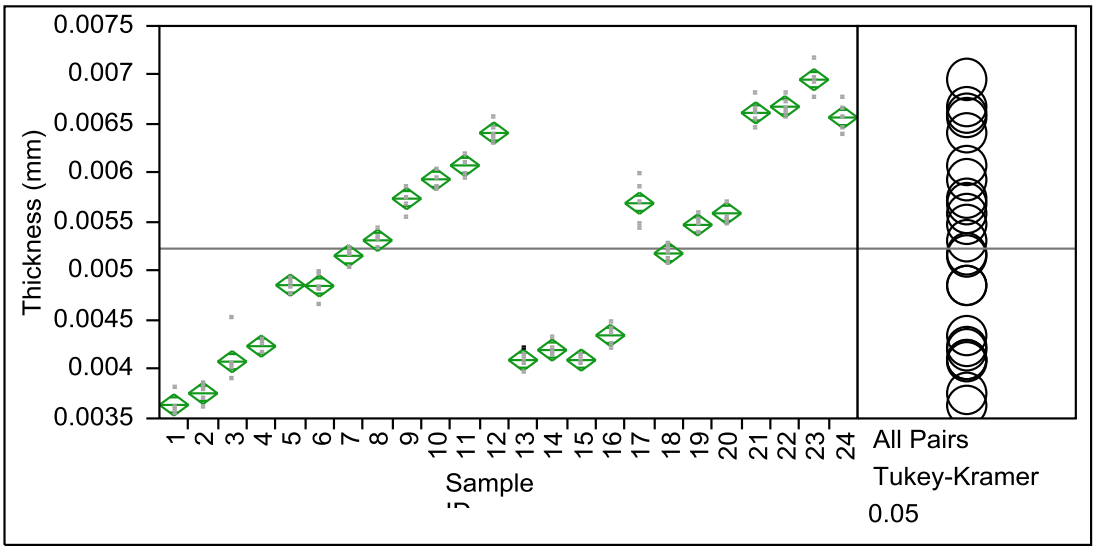


Figure 34 Oneway analysis of thickness by preform construction

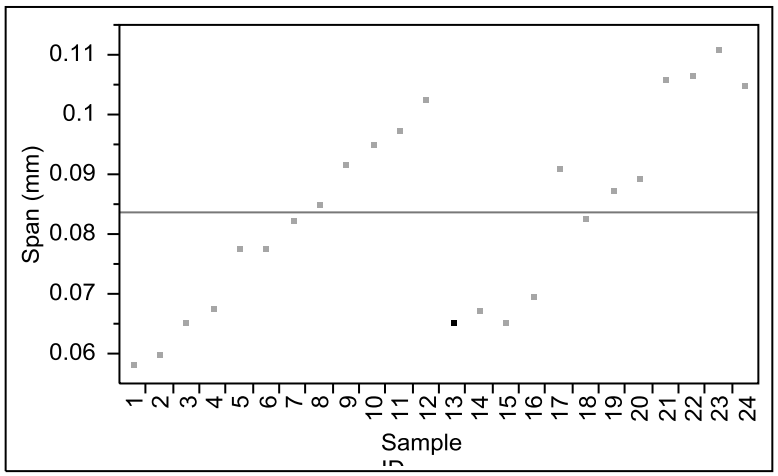
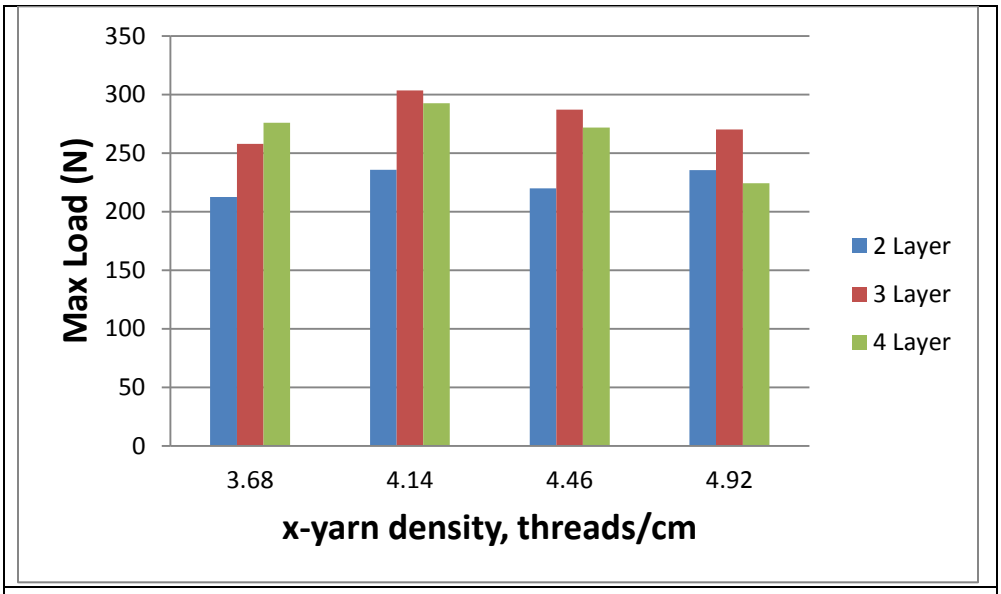


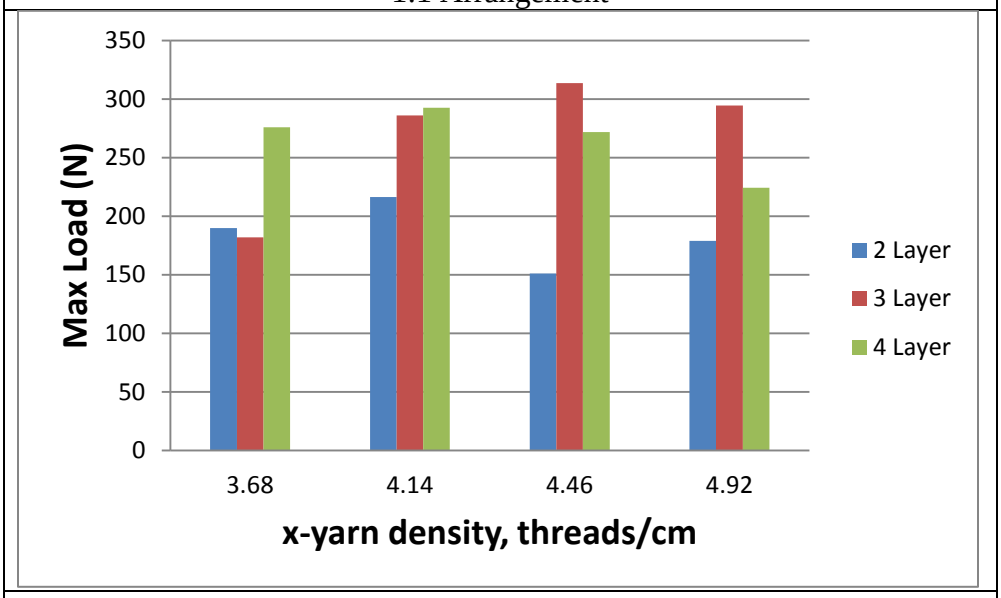
Figure 35 One way analysis of span by preform construction

The increase in span length is determined by the thickness of the specimen, so a thicker specimen requires a wider span for the three point bending flex test. By testing the specimens according to thickness this creates a comparison that is based on construction because the

changing span length accommodates the thickness. This is shown through Figures 36, 37, 38, and 39. In these figures there is no true trend. The highest load and highest stress are shown by the 3 layer structure. The yarn arrangement shows to have a major effect on the results as well. The results for the Max Load for the 1:1arrangement show a decrease with increase of x-yarn density past 4.14 x-yarns/cm/layer in Figures 36 and 37. This expresses an optimal construction for layer and x-yarn density with an arrangement of 1:1. The 2:2 arrangement shows similar trends but is optimized at 4.46 x-yarns/cm/layer with 3 layers for y-direction and 4 layers in the x-direction. Overall the samples show negligible variance from x-direction to y-direction.In the flex load and flex stress of the 1:1 a noticeable decrease with higher x-yarn densities is noticed in the y-direction. This occurrence can be attributed to increased number of oriented ends disallowing movement within the structure. Having higher thread density creates higher directional orientation which in turn creates a stiffer composite. The stiffness relates into less load to break due to the decrease in flexibility of the structure. This also explains the phenomena of the three layer structure having improved properties over four layers. Another contributing factor relating to this instance is the bending radius. Having an extra layer creates a longer distance for the top layer to extend as the bottom layer is contacted. This creates higher stress on a single layer creating a weaker point for composite deformation.



1:1 Arrangement



2:2 Arrangement

Figure 36 Max flex load (N) in terms of construction in y-direction

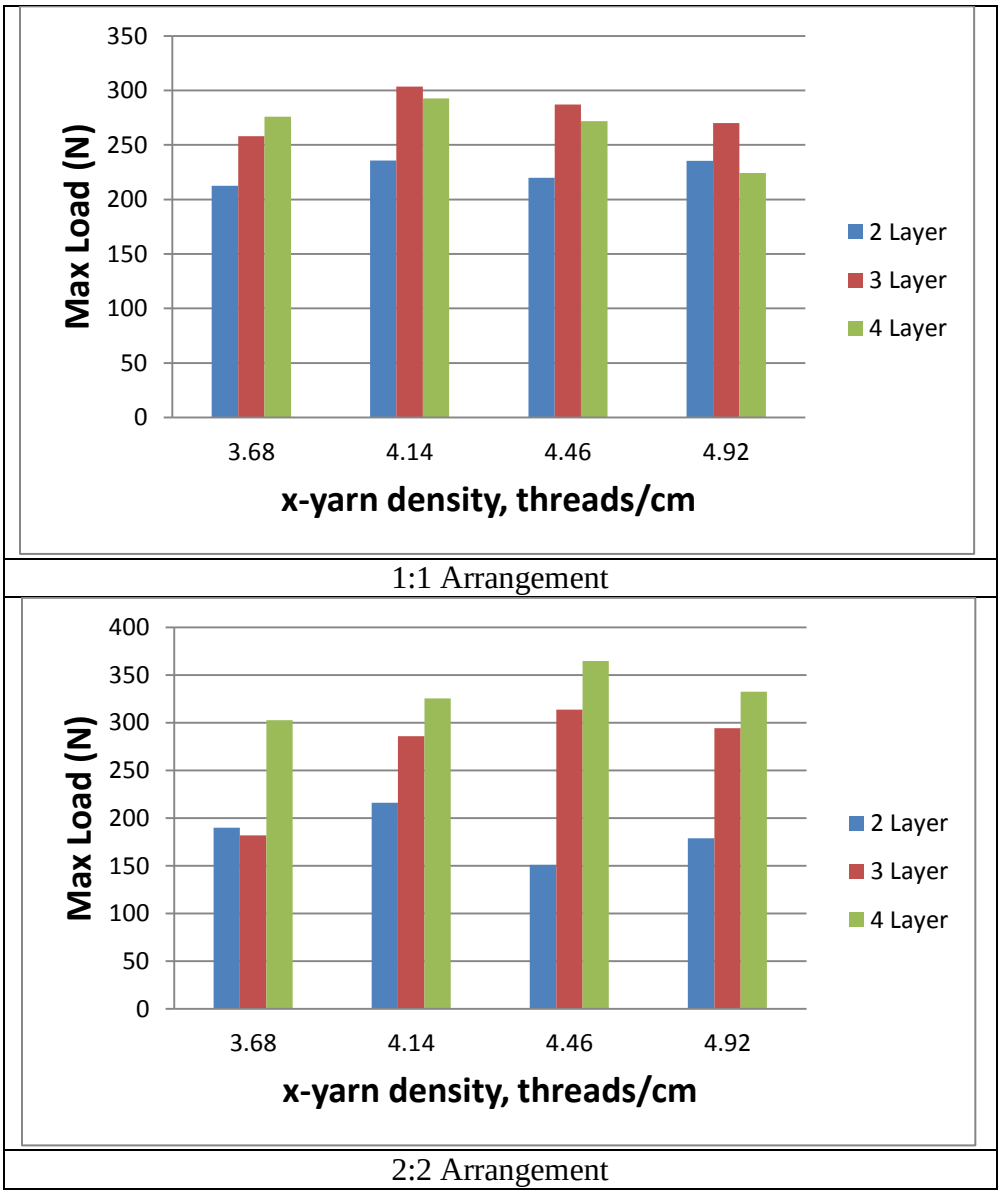
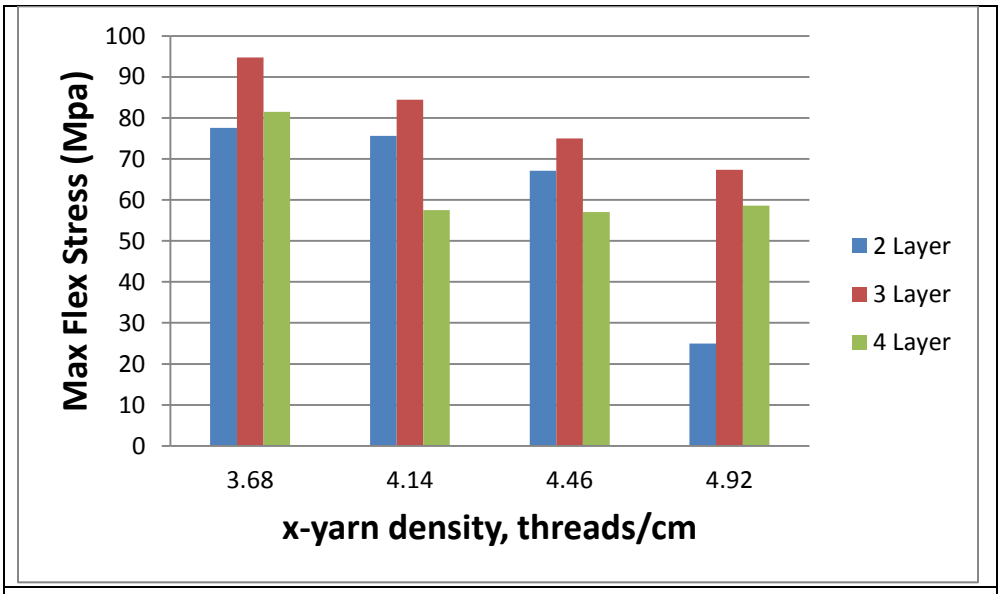
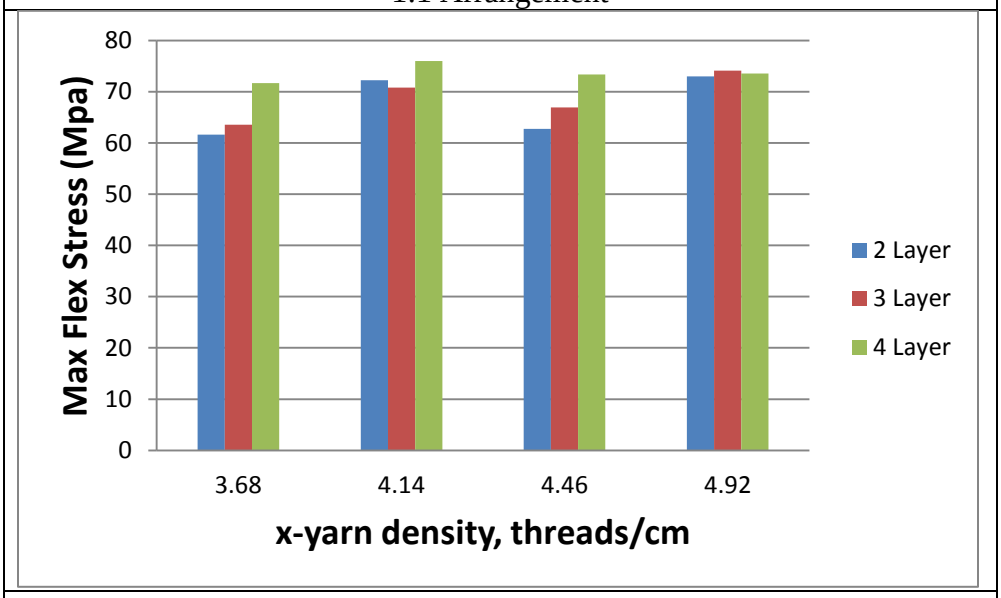


Figure 37 Max flex load (N) in terms of construction in x-direction

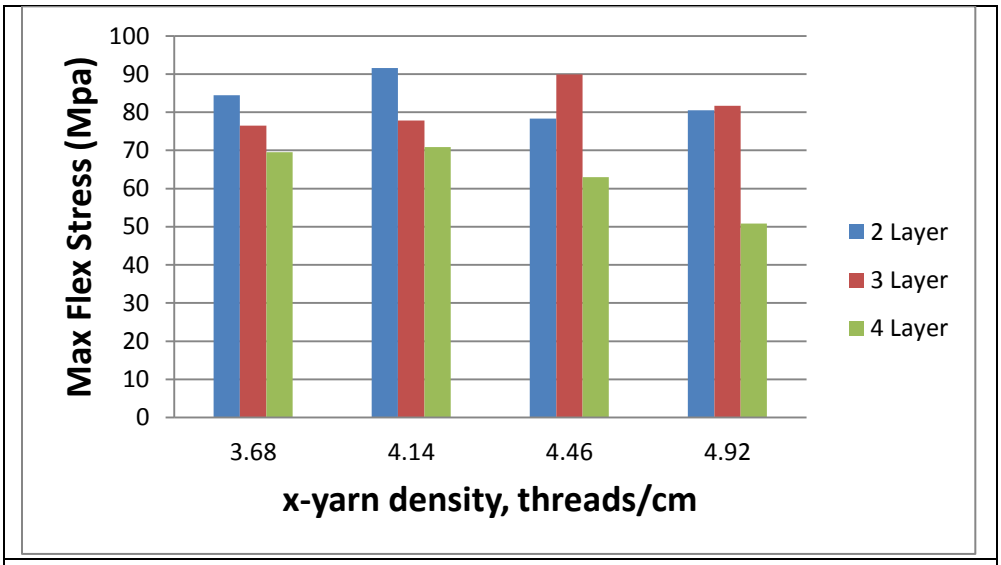


1:1 Arrangement

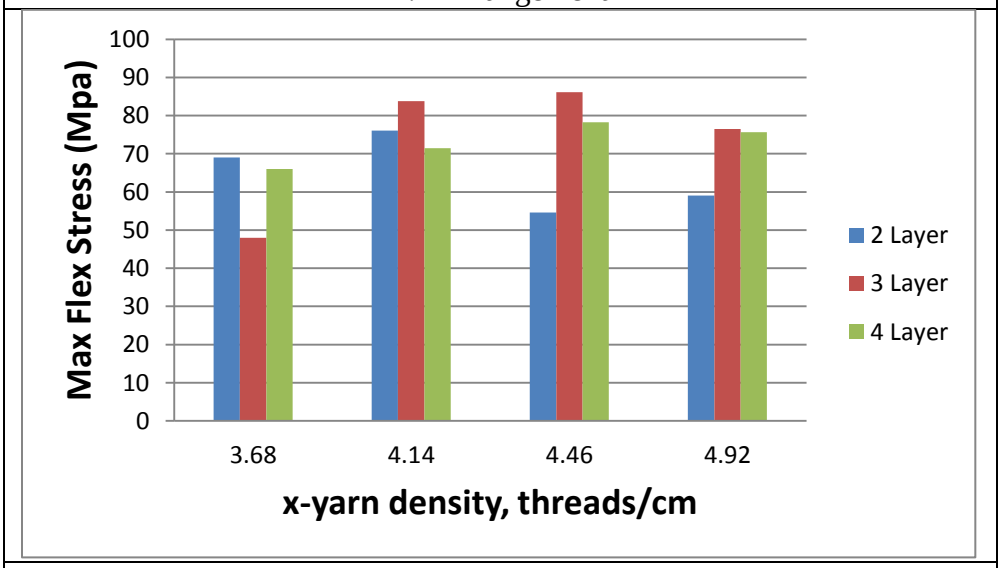


2:2 Arrangement

Figure 38 Analysis of max flex stress (Mpa) in y-direction



1:1 Arrangement



2:2 Arrangement

Figure 39 Analysis of max flex stress (Mpa) in x-direction

6.4 Impact Properties

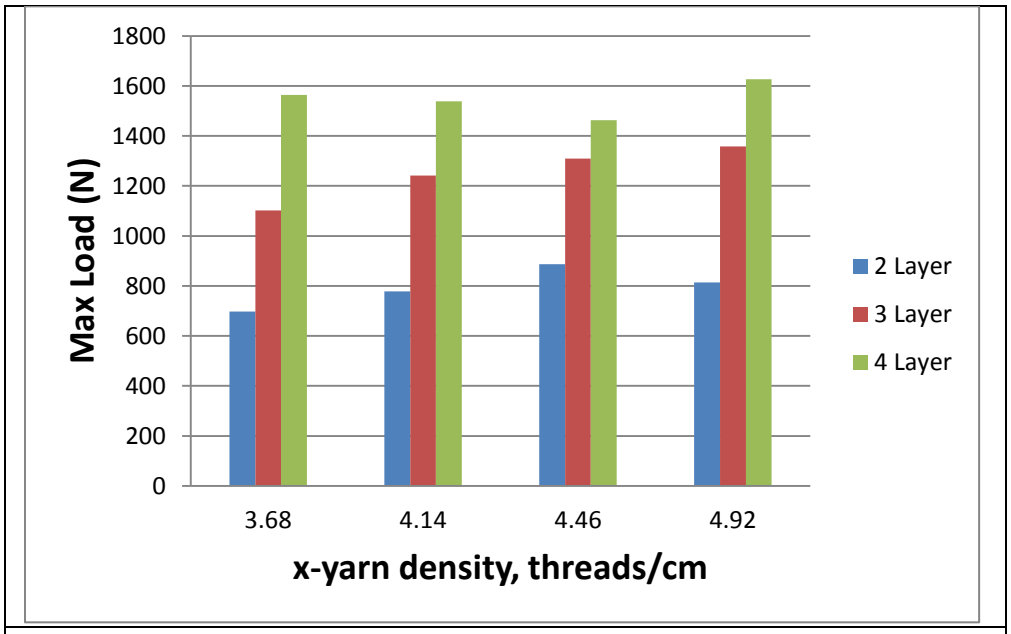
Table 19 shows the impact properties data.

Table 19 Impact resistance results

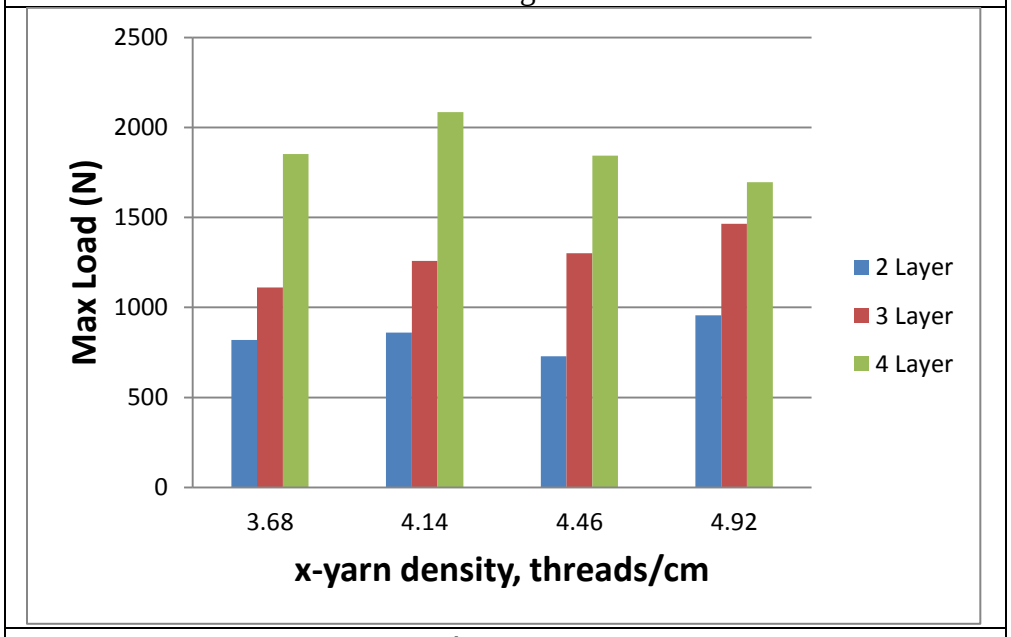
ID	Arrangement (y-yarn : z-yarn)	# of Layers (y/x)	x-yarn density (threads/cm/layer)	Impact Velocity (m/sec)	Max Load (N)	Energy to Max Load (J)	Deflection at Max Load (mm)	Total Energy (J)
1	**1:1**	**2/3**	**3.68**	**4.32**	**698**	**2.37**	**6.21**	**4.96**
2	1:1	2/3	4.14	4.33	778	2.66	6.26	5.38
3	1:1	2/3	4.46	4.31	887	3.47	6.75	5.49
4	1:1	2/3	4.92	4.33	814	2.99	5.82	6.05
5	1:1	3/4	3.68	4.32	1,102	4.89	7.24	9.01
6	**1:1**	**3/4**	**4.14**	**4.33**	**1,242**	**5.32**	**7.07**	**10.17**
7	1:1	3/4	4.46	4.33	1,309	5.53	7.04	9.71
8	1:1	3/4	4.92	4.31	1,358	6.34	7.38	10.61
9	1:1	4/5	3.68	4.32	1,564	7.12	7.42	11.82
10	1:1	4/5	4.14	4.32	1,539	7.44	7.69	13.03
11	**1:1**	**4/5**	**4.46**	**4.33**	**1,463**	**6.87**	**7.46**	**15.00**
12	1:1	4/5	4.92	4.31	1,627	7.08	7.00	15.96
13	**2:2**	**2/3**	**3.68**	**4.30**	**819**	**3.27**	**6.57**	**6.97**
14	2:2	2/3	4.14	4.32	860	3.01	6.02	5.77
15	2:2	2/3	4.46	4.33	729	3.13	6.92	6.08
16	2:2	2/3	4.92	4.32	956	3.29	5.86	7.54
17	2:2	3/4	3.68	4.33	1,112	4.36	6.07	9.76
18	**2:2**	**3/4**	**4.14**	**4.33**	**1,258**	**4.44**	**6.03**	**8.51**
19	2:2	3/4	4.46	4.30	1,300	5.87	7.22	11.17
20	2:2	3/4	4.92	4.31	1,465	5.90	6.73	10.38
21	2:2	4/5	3.68	4.30	1,852	8.20	6.92	14.88
22	2:2	4/5	4.14	4.32	2,086	9.89	7.23	15.26
23	**2:2**	**4/5**	**4.46**	**4.33**	**1,844**	**8.74**	**6.94**	**15.18**
24	2:2	4/5	4.92	4.31	1,696	8.30	7.09	12.80

The impact testing showed more consistent increase in properties with the increase of the x-yarn density and number of layers. The increase of layers increases the thickness of the composites providing a higher impact resistance. This general trend is shown over Figures 40-43. The basic understanding is the more yarn in the structure the better is the impact resistance although the 2:2 yarn arrangement provides very close results to the 1:1 arrangement. The dependence on the amount of yarn present predicts that with higher fiber volume fraction impact results would also improve.

In general the 4 layer structures showed much higher results for max load, energy to max load, and total energy required to break the structure. Looking at Figure 42 the results seem to be much closer in terms of amount of actual deflection. The deformation of the specimens shows less dependence on layers and x-yarn density though it does have minimal increase



1:1 Arrangement



2:2 Arrangement

Figure 40 Analysis of Max Load (N)

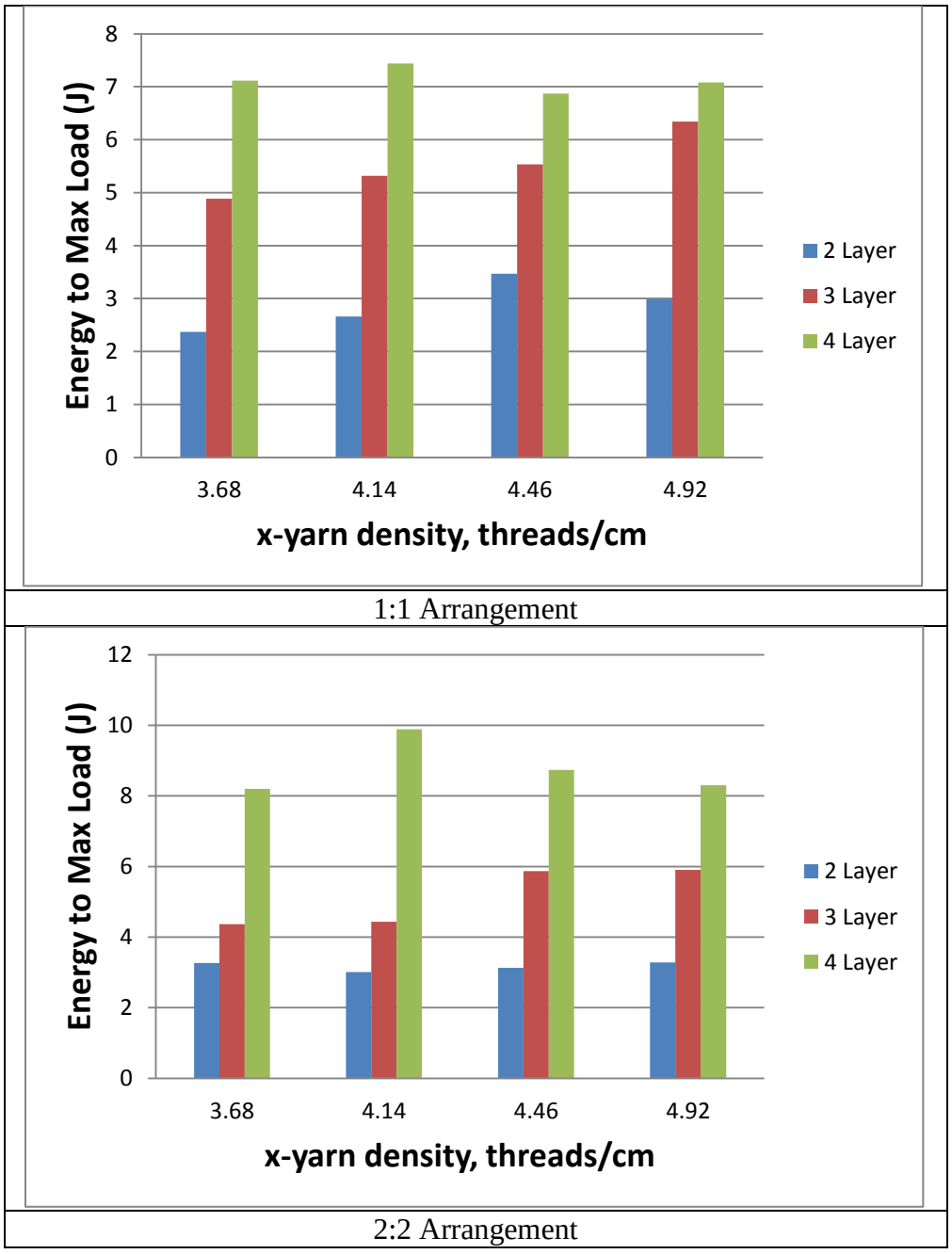
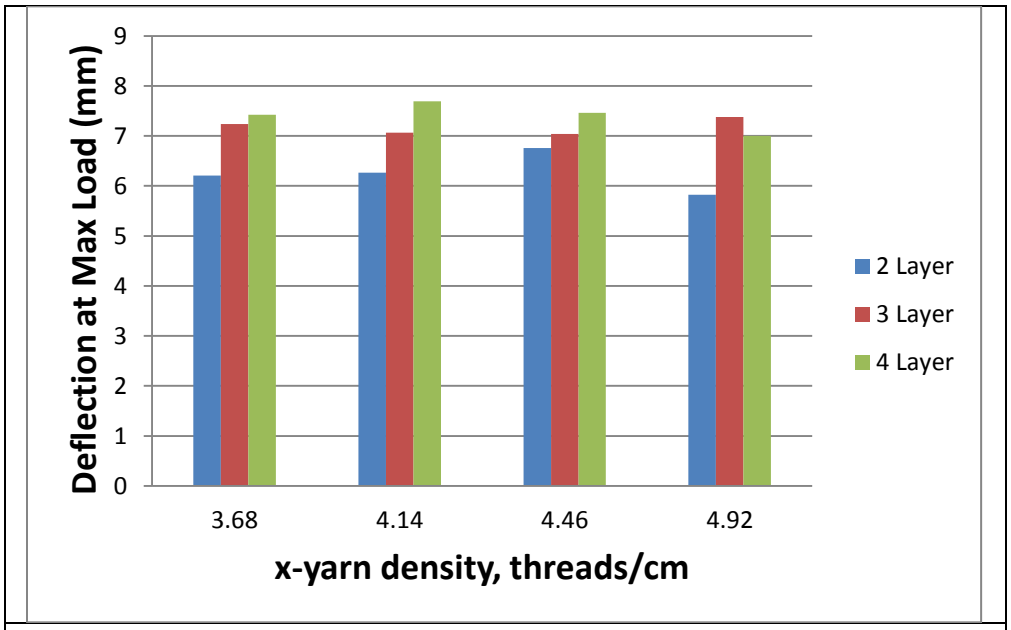
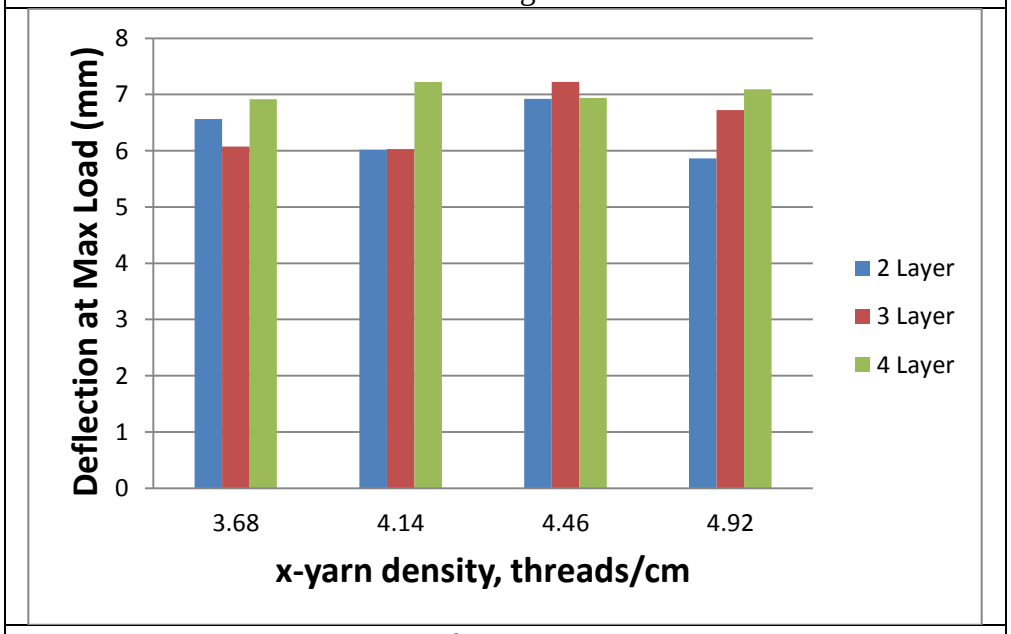


Figure 41 Analysis of energy to max impact load (J)



1:1 Arrangement



2:2 Arrangement

Figure 42 Analysis of deflection at max impact load (mm)

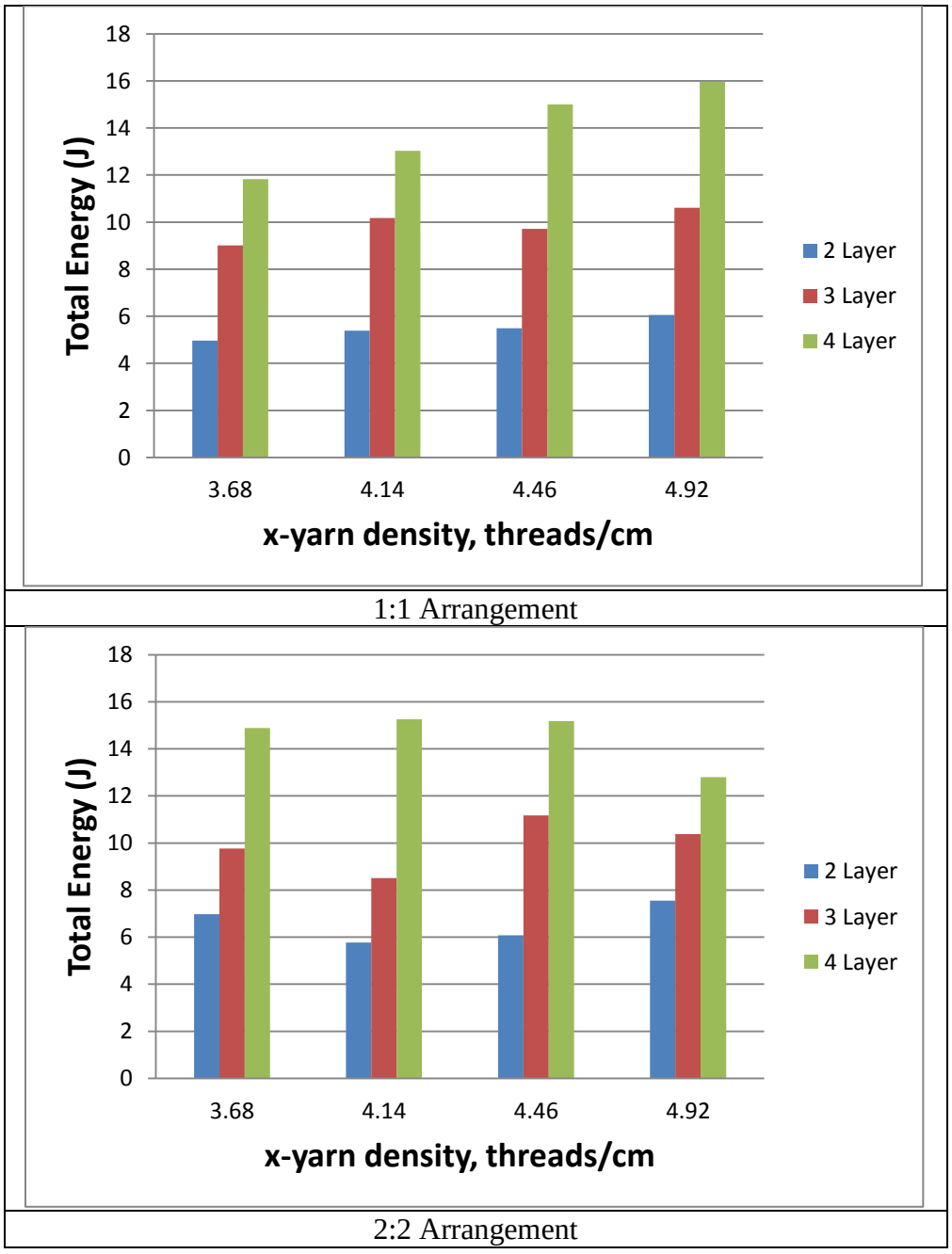


Figure 43 Analysis of total impact energy (J) to break

6.5 Resin Flow Front

In infusing the 24 sample lot for the main experiment an improved method was used to reduce the time of the fow for the resin. A mesh flow media layer was added on top of the sample. The flow media allowed for the resin to flow across the surface of the preforms then absorb through while under pressure. This creates a larger area for the resin to absorb unlike the original method where a majority of the absorption takes place along the thickness of the sample. In Table 20 and Figure 44 the flow front is shown and one can see the increase of infusion time with the increase of the number of layers. There is also a noticeable trend with reference to increasing x-yarn density and increased infusion time. The increased x-yarn density creates a tighter structure creating smaller void areas within the preforms where the resin flow occurs therefore flow is slower.

Comparing the results of resin flow front of Figure 24 to that of Figure 22, it can be noticed that the time of resin flow front has dramatically reduced for the samples of Figure 44 compared to the samples of Figure 22 as a result of using the mesh flow media. However, it was noticed that complete wetting of the samples of the main experiment (of Figure 44) was not achieved despite the resin travelled all the way from the inlet to the outlet. To achieve complete wetting each sample was kept in the vacuum bag for 60 minutes a matter that allowed the resin to go through the thickness. This time was fixed for each sample regardless of the construction and it was noticed that the time is enough for complete wetting of the most dense and thick samples. The optimum time (shortest) for complete wetting varies from sample to another depending on the construction, a study to reveal the optimum time for each construction is worth researching.

Table 20 Total time for the resin to flow through the sample

Sample ID	Arrangement (y-yarn : z-yarn)	# of Layers (y/x)	x-yarn density (threads/cm/layer)	Resin Flow Front Total Time (min)
1	**1:1**	**2/3**	**3.68**	**1.367**
2	1:1	2/3	4.14	1.217
3	1:1	2/3	4.46	1.400
4	1:1	2/3	4.92	1.567
5	1:1	3/4	3.68	1.450
6	**1:1**	**3/4**	**4.14**	**3.033**
7	1:1	3/4	4.46	1.183
8	1:1	3/4	4.92	2.600
9	1:1	4/5	3.68	1.067
10	1:1	4/5	4.14	2.350
11	**1:1**	**4/5**	**4.46**	**2.067**
12	1:1	4/5	4.92	2.383
13	**2:2**	**2/3**	**3.68**	**3.683**
14	2:2	2/3	4.14	3.700
15	2:2	2/3	4.46	3.850
16	2:2	2/3	4.92	3.917
17	2:2	3/4	3.68	3.050
18	**2:2**	**3/4**	**4.14**	**3.533**
19	2:2	3/4	4.46	4.617
20	2:2	3/4	4.92	4.983
21	2:2	4/5	3.68	2.583
22	2:2	4/5	4.14	3.533
23	**2:2**	**4/5**	**4.46**	**3.700**
24	2:2	4/5	4.92	4.317

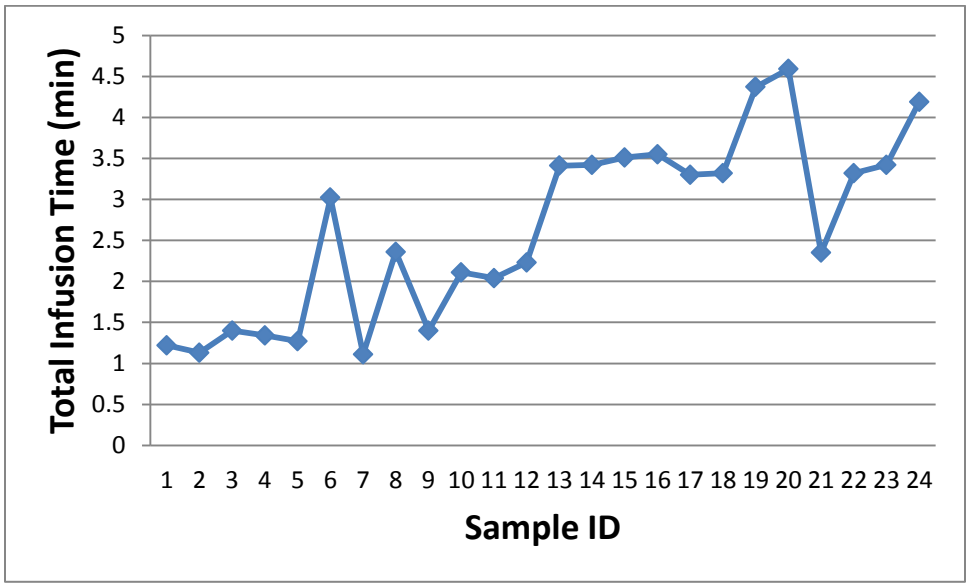


Figure 44 Total infusion time by sample ID Envirez 86400INF

6.6 Benchmarking of Bio-Composites

6.6.1 Tensile Properties of Composites from Fiberglass

Fiberglass samples were woven with the same 1:1 y to z yarn arrangement to the bio composite constructions previously discussed. The fiberglass preforms were infused with the same equipment under the same parameters using Derakane 8084 Epoxy resin. The samples were woven with 4 layers at three x-yarn densities to create multiple structures for comparison with cotton/bio composites. The fiberglass and cotton composites constructions are depicted in Table 21.

Table 21 Fiberglass Sample Construction and physical properties

Sample ID	# of Layers (Y/X)	X-yarn density (threads per cm)	Resin Type	Thickness (mm)	Preform Weight (g/cm^2)	Composite Weight (g/cm^2)	Fiber Volume Fraction (%)
Glass/Epoxy Composites							
1G	4/5	2	Epoxy	2.7	0.30	0.41	66.6
2G	4/5	3.5	Epoxy	3.2	0.35	0.48	66.1
3G	4/5	5	Epoxy	3.3	0.40	0.53	67.5
Cotton/Bio-Resin Composites							
1C	4/5	4.14	Bio	4.17	0.14	0.52	26.0
2C	4/5	4.46	Bio	4.29	0.13	0.51	26.0
3C	4/5	4.92	Bio	4.09	0.14	0.52	26.0

Fixed parameters for 1G-3G samples are:

Linear Density x-yarns: 735 (g/km or tex)
Linear Density y- yarn: 2275 (g/km or tex)
Linear Density z-yarns: 276 (g/km or tex)
y-yarn : z-yarn arrangement: 1:1

Fixed parameters for 1C-3C samples are:

Linear Density x-yarns: 300 (g/km or tex)
Linear Density y- yarn: 689 (g/km or tex)
Linear Density z-yarns: 300 (g/km or tex)
y-yarn : z-yarn arrangement: 1:1

The textile preforms as well as finished composite panels were tested to gather data for detailed evaluation. The testing standards used for the cotton/bio composites were followed in testing the fiberglass composites to allow comparison between the constructions. The composite properties were normalized based on the fiber volume fraction. Tables 22-25 and Figures 45-54 display the normalized data.

Table 22 Y-direction tensile property comparison

Sample ID	Thickness (mm)	Width (mm)	Max Load (N)	Mas Stress (Mpa)	Tensile strain at Maximum Load (%)
1G	2.79	25.4	45,799	651.04	9.45
2G	3.24	25.4	45,486	554.34	8.75
3G	3.33	30.4	51,549	526.59	10.02
1C	3.86	25.4	4,604	43.6	7.93
2C	3.99	25.4	4,697	43.2	7.21
3C	4.29	25.4	4,788	46.1	7.48

Table 23 X-direction tensile property comparison

Sample ID	Thickness (mm)	Width (mm)	Max Load (N)	Stress at Max (Mpa)	Tensile strain at Maximum Load (%)
1G	2.54	254.0	12201	188.6	6.04
2G	3.23	254.0	21922	263.6	7.13
3G	3.37	254.0	27972	326.5	7.49
1C	4.17	25.4	3,450	35.1	7.53
2C	4.29	25.4	4,269	42.3	8.24
3C	4.09	25.4	4,310	39.6	8.18

The small increase in x-yarn density in the preform show little effect on the thickness which should be apparent in the mechanical properties. The differences seen in the Max Load between the orientations are shown to have much higher y-direction strength with an average of approximately 48,000 N and the x-direction only taking 21,000 N which is an approximate 43% decrease in strength. With the increasing x-yarn density there is an increase in strength shown in the x-direction while the strength shows to decrease with the higher number of x-yarns when tested in the y-direction. The comparison of tensile load of the fiberglass and cotton/bio composites is shown in Figures 45 and 46. There is a noticeable difference in max load between the composite types on average the cotton/bio composites handle only 10% of the load of the

fiberglass. This is also seen in the comparison of stress at max load in Figures 47 and 48. The strain comparison, on the other hand showed very similar results between the two composite structures. In Figures 49 and 50 the strain (or amount of stretch) being so similar provides insight that proves that the two materials have similar displacement properties.

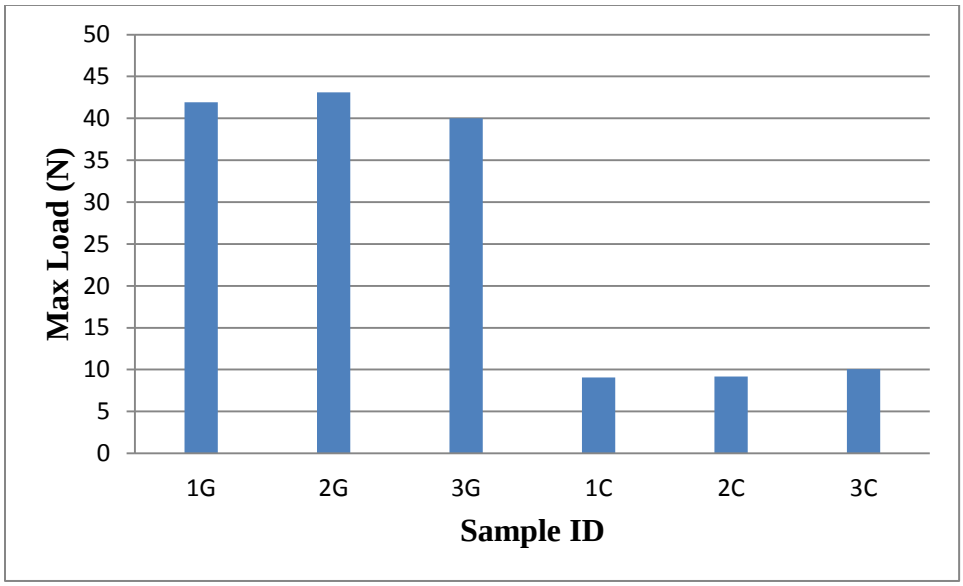


Figure 45 Comparison of tensile load at max (N) in y-direction

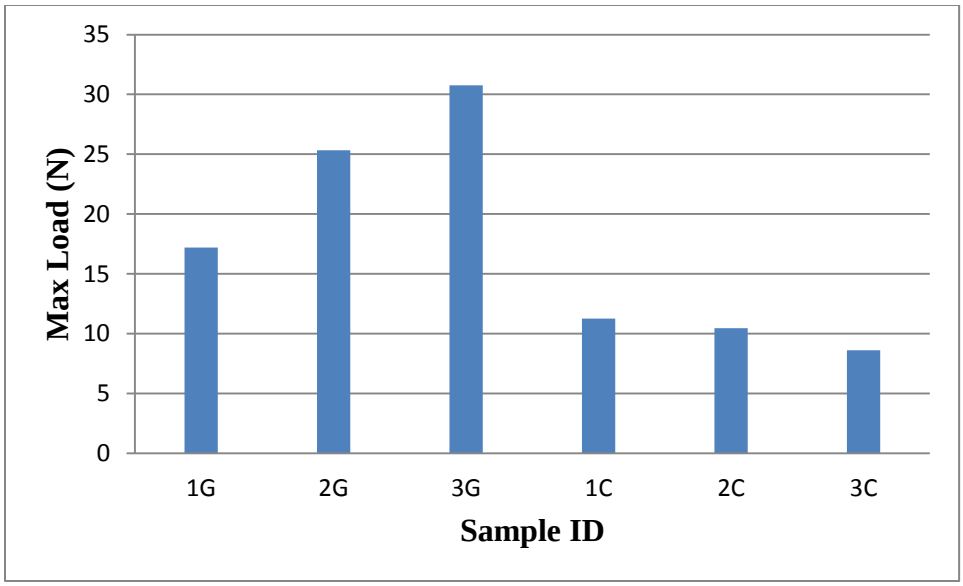


Figure 46 Comparison of tensile load at max (N) in x-direction

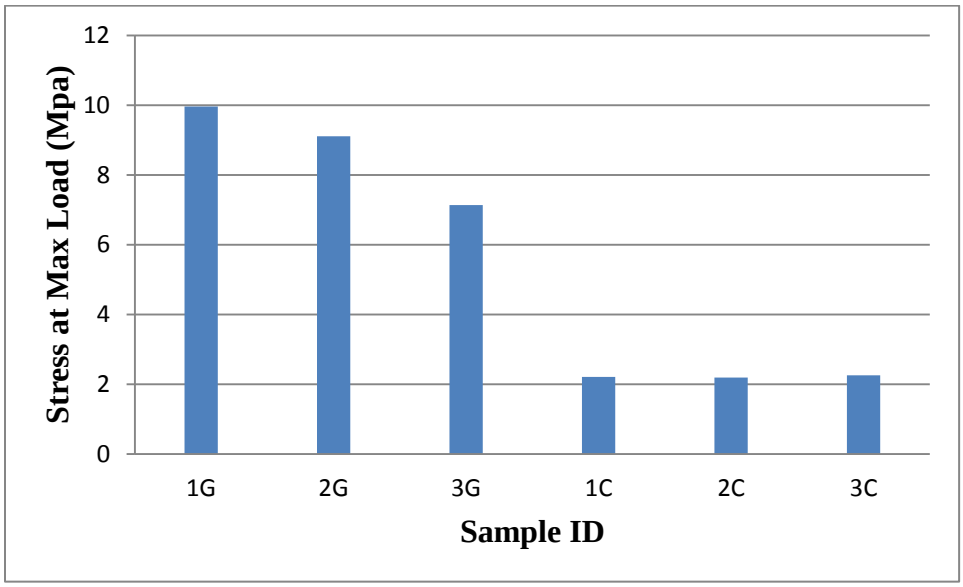


Figure 47 Comparison of tensile stress at max load (Mpa) in y-direction

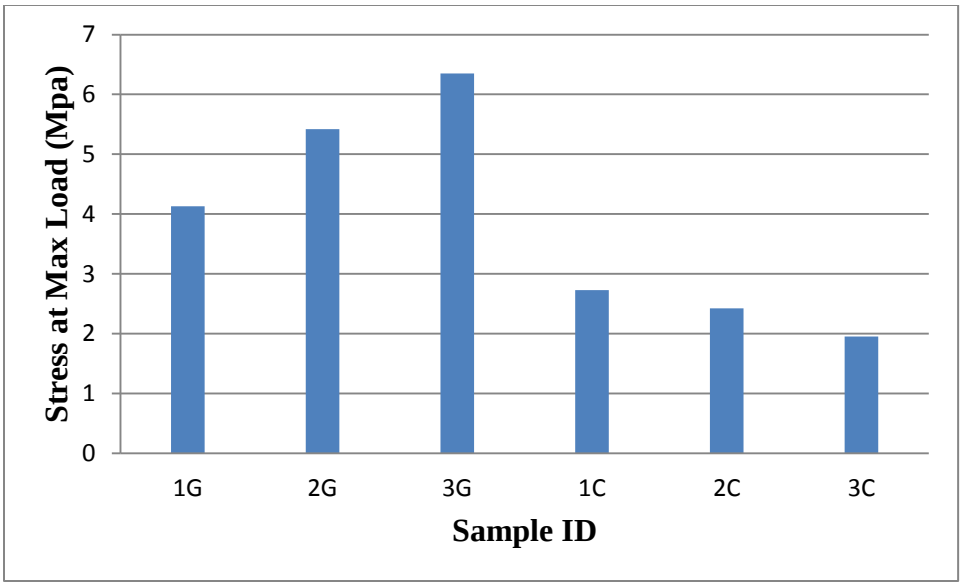


Figure 48 Comparison of tensile stress at max load (Mpa) in x-direction

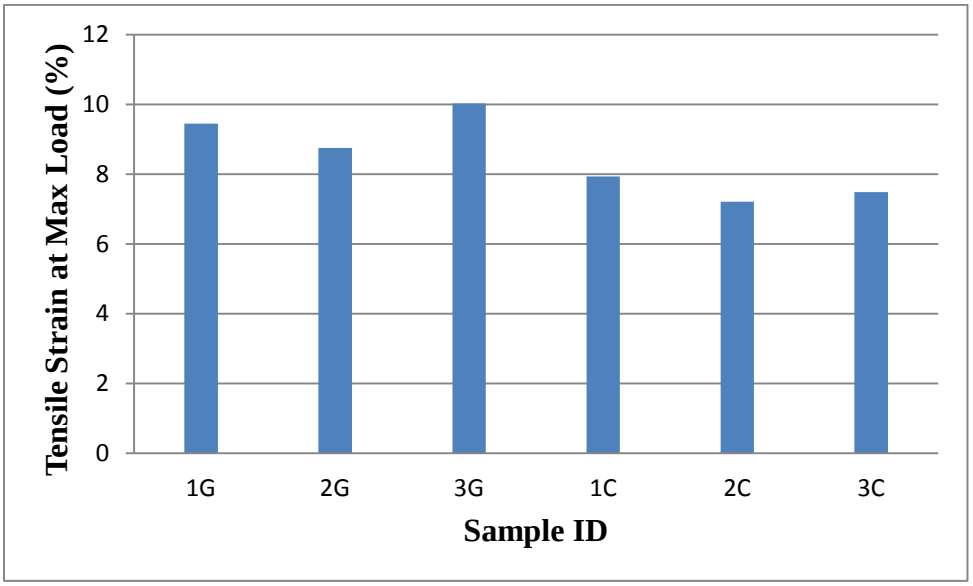


Figure 49 Comparison of tensile strain at max load in y-direction

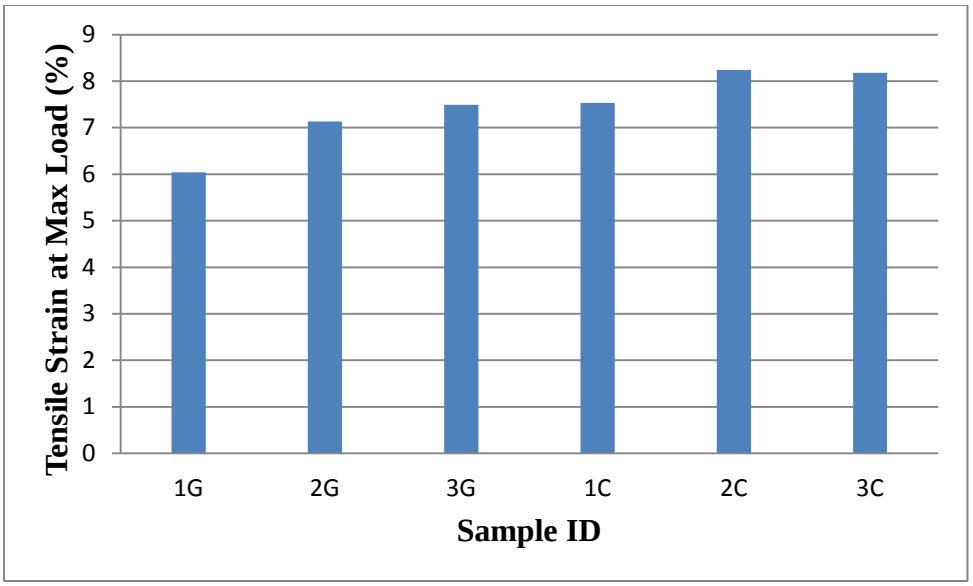


Figure 50 Comparison of tensile strain at max load in x-direction

6.6.2 Fiberglass Flex Properties

The comparison of the flexural properties of the two composite types showed very different results from the tensile testing (Tables 23 and 24). In Figure 53 the flex Max Load for fiberglass increases with increased x-yarn density while the cotton/bio composites decrease for the x-direction samples. This phenomena is also seen in the stress results for x-direction testing (Figure 54). The opposite trend is seen in the y-direction testing shown in Figures 51 and 52.

Table 24 Y-direction flex property comparison

Sample ID	Width (mm)	Depth (mm)	Span (mm)	Load @ Max (N)	Flexure Stress at Max Load (Mpa)	Young's Modulus (Automatic Limit) (Mpsi)
1G	35.5	2.84	45.5	2791	663.3	2.764
2G	35.5	3.21	51.3	2849	601.9	2.240
3G	35.5	3.78	60.7	2700	481.9	2.099
1C	25.7	3.84	61.2	236	57.5	0.42
2C	25.6	3.91	62.7	239	57	0.441
3C	25.8	4.14	66.2	261	58.6	0.427

Table 25 X-direction flex property comparison

Sample ID	Width (mm)	Depth (mm)	Span (mm)	Load @ Max (N)	Flexure Stress at Max Load (Mpa)	Young's Modulus (Automatic Limit) (Mpsi)
1G	35.5	2.76	44.2	1146	275.0	1.683
2G	35.5	3.16	50.5	1675	358.1	1.910
3G	35.5	3.28	52.3	2076	428.6	2.329
1C	25.7	3.86	61.7	293	70.9	0.453
2C	25.6	4.06	65.0	272	63	0.426
3C	25.8	4.14	66.0	224	50.8	0.442

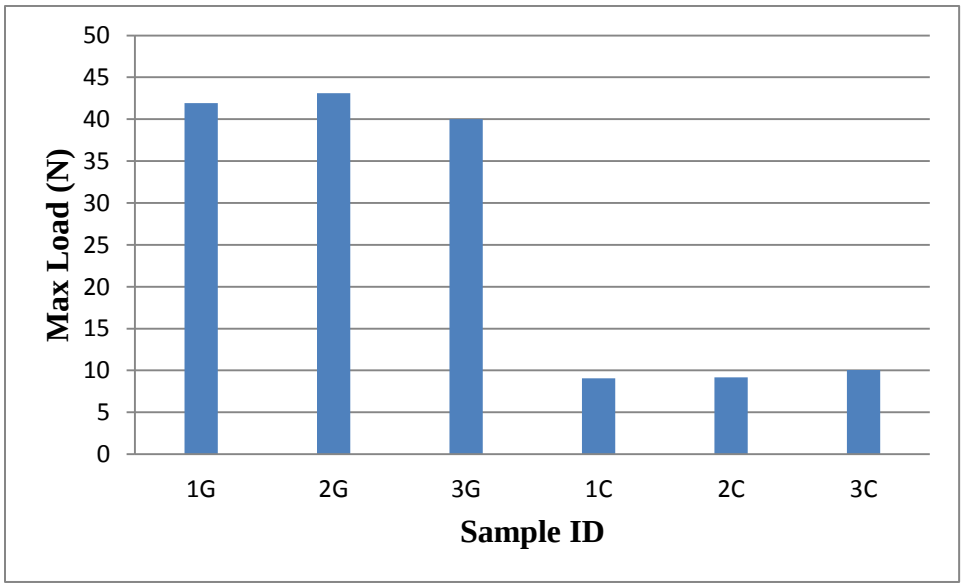


Figure 51 Y-direction comparison of flex load at max (N)

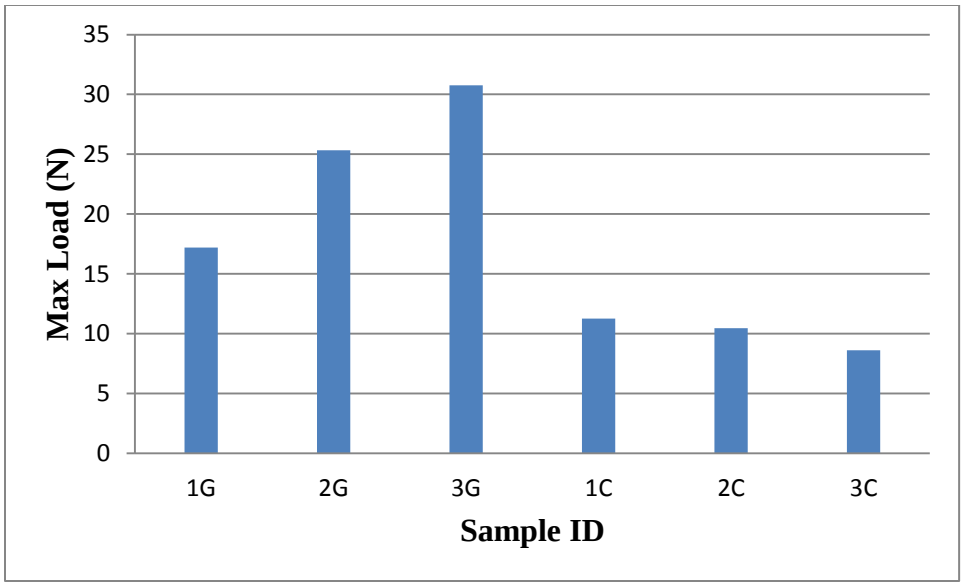


Figure 52 Y-direction comparison of flexure stress at max load (Mpa)

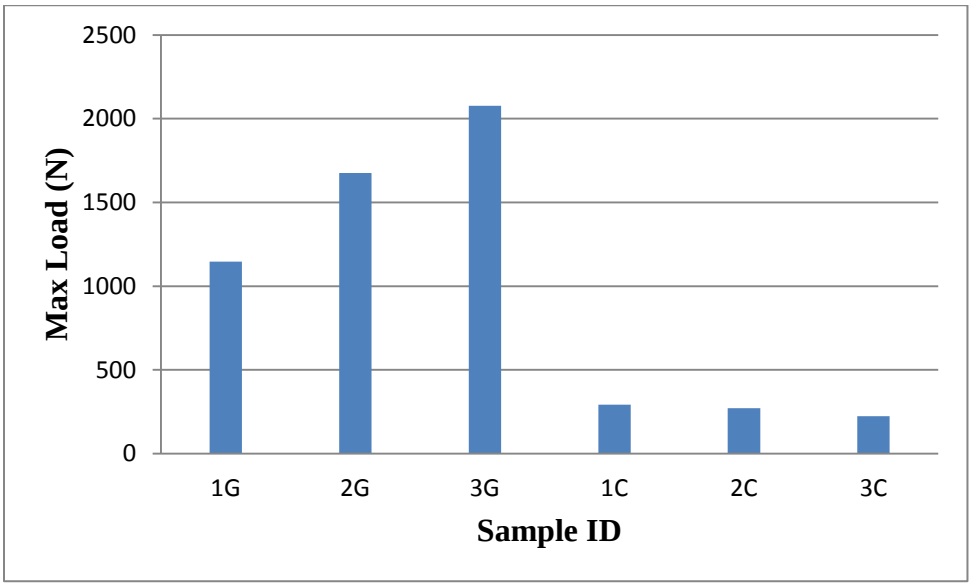


Figure 53 X-direction comparison of flex load at max (N)

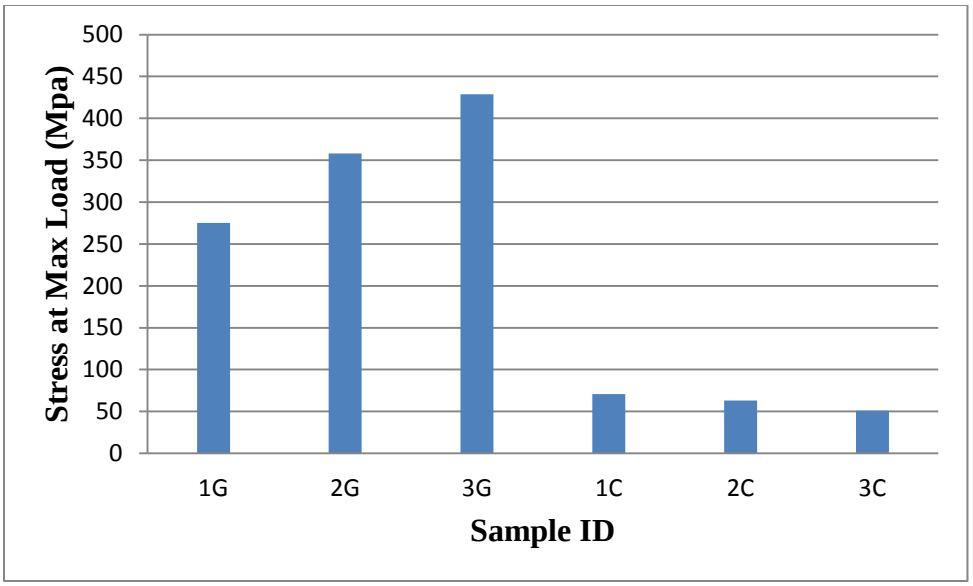


Figure 54 X-direction comparison of flexure stress at max load (Mpa)

6.8 Failure Analysis

The failure mode of each sample was observed and recorded during each testing method used. In Figure 59 the failure of the tensile testing is shown. During this test the failure mode seen was tension failure. Failure happened in the center of the sample between the testing grips not at or in the gripped area proving that the sample was breaking due to the tension load. At break the samples broke cleanly through not leaving and connection between the two ends of the specimen. Breaking directly across proves that the bio-resin and the cotton yarns shared the load well and the resin did not fail early. This phenomena was also seen in flex testing failure shown in Figure 61. Further, the two ends of the specimen were intact after failure on the compression side.

Impact failure was observed as well as shown in Figure 60. It was observed during the testing that with increased number of layers the deformation at impact increased in area. Each sample was punctured through and no abnormalities were observed.

Figure 59 Tensile test failure

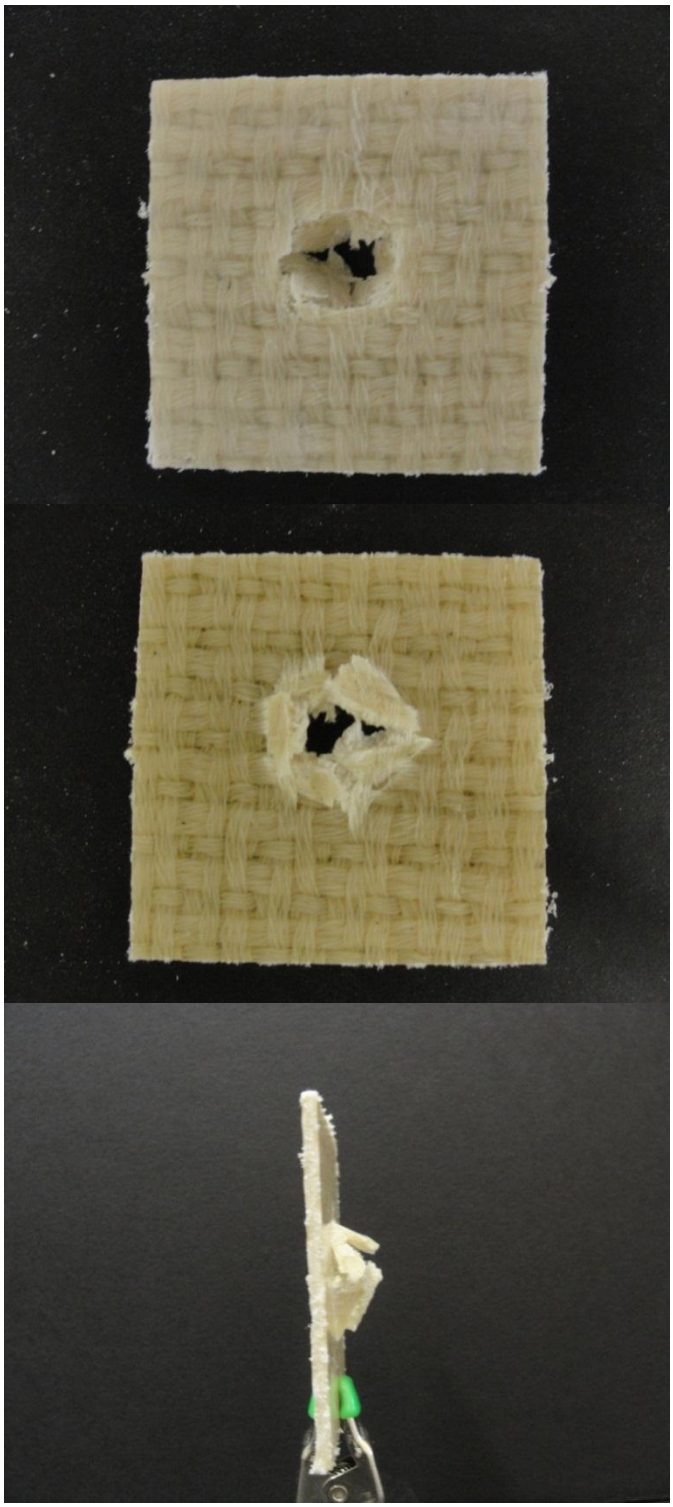


Figure 60 Impact test failure

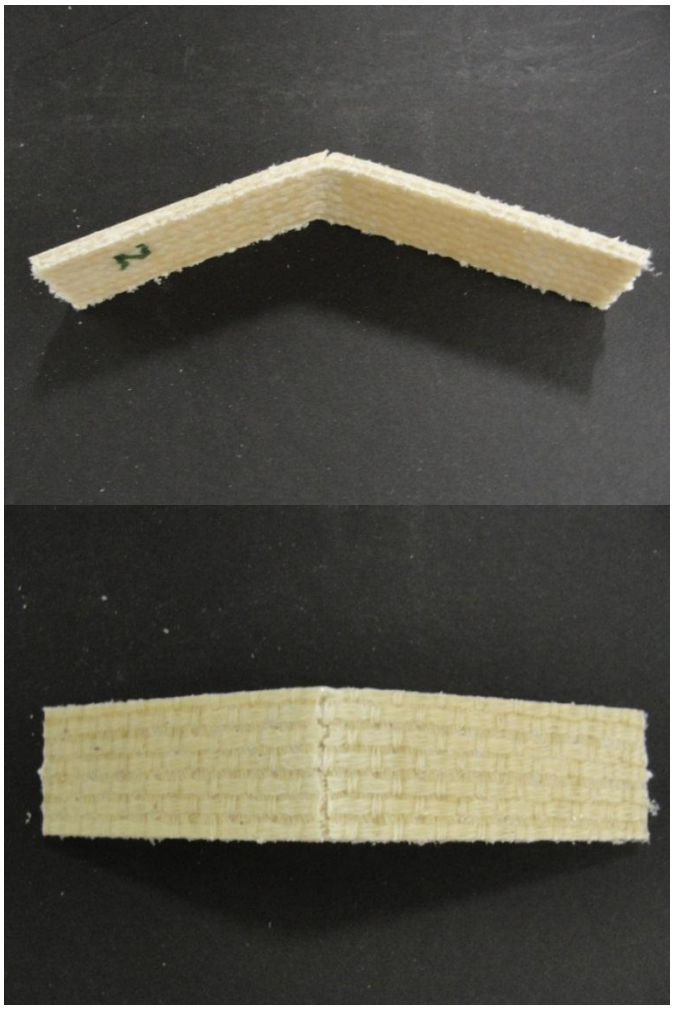


Figure 61 Flex test failure

7. Conclusions

We successfully produced composite panels using 3D weaving technology and vacuum infusion method for both epoxy and bio-based resins. From the testing results the cotton preform composites have the effective specific property values of approximately 10-15% of the same constructions of fiberglass. The cotton preforms were also very dependent on the number of

layers in the construction more so than the x-yarn density. Although the strength of these composites is not within the accepted category of ‘high-performance’ they are still beneficial on the sustainable front. There are many markets that need ‘green’ products that meet certain application standards that fiberglass composites would be over-engineered for such markets. The ability to further this research with higher strength natural fibers along with bio-based resins that are rapidly improving in their ability to be processed and mechanical properties create the potential to ‘tailor’ a natural composite for numerous application.

8. Future Work

Further development of woven natural composites should approach different fiber types. Literature review disclosed that higher strength natural fibers were found in abundance. This would allow for higher performance composites to be produced while maintaining the sustainable side of using natural fibers and bio-based resins. In chapter 1 natural fibers were discussed such as flax that have equal or higher specific properties to that of many fiberglass compositions. Having a fiber with higher initial properties will provide a better reinforcement creating a higher strength composite. Increasing the fiber volume fraction beyond what is achieved in this research is expected to provide higher composite performance. Another aspect that needs further work is the preform construction. There was an apparent lose in strength with increasing x-yarn densities to a certain point. Research needs to be done to develop the most stable structure for the 3D woven preforms.

Another issue is related to standard sample dimensions. For example, the sample width for tensile and flexural properties is 25 mm. In observing the cut samples this dimension causes the yarns to be cut in fractions, which contributes to larger errors when dealing with small yarn density than larger yarn density. This needs to be looked at by the test standard developers.

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APPENDICES

Appendix A

Table B.1 Raw data for y-direction tensile test

	Thickness (in)	Width (in)	Maximum Load (lbf)	Max Load (N)	Max Load (kN)	Stress@ Max (ksi)	Max Stress (Mpa)	Tensile strain at Maximum Load (%)
2ld4.67	0.098	1	564.5471	2511.2297	2.5112297	5.78	39.851697	6.2898
2ld4.67	0.104	1	522.2694	2323.1692	2.3231692	5.02	34.611682	4.8698
2ld4.67	0.102	1	636.486	2831.2298	2.8312298	6.24	43.023286	6.6217
2ld4.67	0.103	1	673.1292	2994.2268	2.9942268	6.55	45.16066	7.1963
2ld4.67	0.133	1	665.1992	2958.9524	2.9589524	5.01	34.542734	5.2759
2ld5.25	0.105	1	582.7258	2592.0926	2.5920926	5.55	38.265903	5.7136
2ld5.25	0.102	1	562.5501	2502.3466	2.5023466	5.53	38.128008	5.4366
2ld5.25	0.109	1	659.3342	2932.8636	2.9328636	6.07	41.851177	6.9824
2ld5.25	0.103	1	562.4485	2501.8947	2.5018947	5.45	37.576427	5.9131
2ld5.25	0.11	1	687.5821	3058.5164	3.0585164	6.26	43.161181	6.9195
2ld5.67	0.102	1	445.4185	1981.3195	1.9813195	4.38	30.199037	9.5997
2ld5.67	0.101	1	481.8732	2143.478	2.143478	4.79	33.025887	7.1078
2ld5.67	0.1	1	464.6119	2066.6959	2.0666959	4.63	31.922726	6.2169
2ld5.67	0.096	1	451.7761	2009.5995	2.0095995	4.68	32.267464	5.9204
2ld5.67	0.099	1	486.2141	2162.7873	2.1627873	4.91	33.853258	6.6202
2ld6.25	0.108	1	557.4095	2479.4801	2.4794801	5.18	35.714843	5.8422
2ld6.25	0.108	1	533.4734	2373.007	2.373007	4.96	34.197996	6.2531
2ld6.25	0.109	1	559.7538	2489.908	2.489908	5.11	35.23221	6.2901
2ld6.25	0.106	1	565.6191	2515.9982	2.5159982	5.32	36.680109	6.4326
2ld6.25	0.104	1	489.3672	2176.813	2.176813	4.69	32.336412	5.322
2ls4.67	0.088	1	493.9035	2196.9914	2.1969914	5.58	38.472746	6.6758
2ls4.67	0.092	1	483.6674	2151.459	2.151459	5.28	36.404319	6.6933
2ls4.67	0.096	1	524.0812	2331.2285	2.3312285	5.43	37.438532	8.2933
2ls4.67	0.091	1	458.1703	2038.0423	2.0380423	5.03	34.680629	5.9365
2ls4.67	0.091	1	443.2074	1971.484	1.971484	4.88	33.646416	6.8058
2ls5.25	0.093	1	518.2896	2305.4662	2.3054662	5.59	38.541693	6.5838
2ls5.25	0.096	1	498.983	2219.5862	2.2195862	5.2	35.852738	6.797
2ls5.25	0.094	1	485.3717	2159.0401	2.1590401	5.18	35.714843	5.5291
2ls5.25	0.093	1	469.3396	2087.7258	2.0877258	5.06	34.887472	5.2487
2ls5.25	0.095	1	473.0031	2104.0218	2.1040218	4.98	34.335891	5.9101
2ls5.67	0.108	1	527.5584	2346.6958	2.3466958	4.9	33.784311	5.8548
2ls5.67	0.102	1	461.6871	2053.6858	2.0536858	4.52	31.164303	4.93
2ls5.67	0.105	1	445.7119	1982.6246	1.9826246	4.23	29.164823	4.9446
2ls5.67	0.1	1	509.9899	2268.5473	2.2685473	5.07	34.956419	5.379
2ls5.67	0.107	1	549.6074	2444.7746	2.4447746	5.13	35.370105	6.885
2ls6.25	0.121	1	452.713	2013.767	2.013767	3.75	25.85534	7.6022

2ls6.25	0.114	1	441.483	1963.8135	1.9638135	3.87	26.682711	5.1645
2ls6.25	0.118	1	461.7197	2053.8308	2.0538308	3.93	27.096396	6.3238
2ls6.25	0.113	1	459.3292	2043.1973	2.0431973	4.06	27.992715	6.2825
2ls6.25	0.11	1	463.4645	2061.5921	2.0615921	4.22	29.095876	6.5405
3ld4.67	0.135	1	794.3829	3533.5899	3.5335899	5.89	40.61012	5.9724
3ld4.67	0.134	1	891.3933	3965.1135	3.9651135	6.63	45.712241	7.228
3ld4.67	0.132	1	751.9318	3344.7581	3.3447581	5.68	39.162221	6.3054
3ld4.67	0.135	1	786.9528	3500.5392	3.5005392	5.81	40.05854	7.1662
3ld4.67	0.138	1	794.7802	3535.3572	3.5353572	5.74	39.575907	6.7639
3ld5.25	0.131	1	820.8852	3651.478	3.651478	6.27	43.230128	7.2134
3ld5.25	0.124	1	745.5562	3316.398	3.316398	5.99	41.299596	7.3146
3ld5.25	0.118	1	942.899	4194.2222	4.1942222	8.01	55.227006	8.7501
3ld5.25	0.125	1	911.4147	4054.1731	4.0541731	7.27	50.124886	8.067
3ld5.25	0.119	1	761.2909	3386.3894	3.3863894	6.4	44.126447	7.1312
3ld5.67	0.137	1	943.9113	4198.7251	4.1987251	6.9	47.573825	7.9143
3ld5.67	0.136	1	849.8269	3780.217	3.780217	6.27	43.230128	6.8509
3ld5.67	0.135	1	874.7313	3890.9973	3.8909973	6.48	44.678027	7.627
3ld5.67	0.132	1	812.2632	3613.1254	3.6131254	6.15	42.402757	7.4872
3ld5.67	0.137	1	815.8685	3629.1626	3.6291626	5.96	41.092753	6.7638
3ld6.25	0.14	1	785.8266	3495.5296	3.4955296	5.61	38.679588	6.945
3ld6.25	0.134	1	744.1526	3310.1545	3.3101545	5.53	38.128008	6.1337
3ld6.25	0.14	1	818.8604	3642.4712	3.6424712	5.84	40.265383	6.8224
3ld6.25	0.141	1	842.7246	3748.6244	3.7486244	5.99	41.299596	7.6004
3ld6.25	0.136	1	774.6912	3445.9969	3.4459969	5.7	39.300117	7.0198
3ls4.67	0.123	1	723.3784	3217.7463	3.2177463	5.9	40.679068	6.6535
3ls4.67	0.131	1	847.1272	3768.2082	3.7682082	6.44	44.402237	8.1385
3ls4.67	0.126	1	744.7128	3312.6464	3.3126464	5.93	40.885911	6.7918
3ls4.67	0.125	1	751.1806	3341.4166	3.3414166	6.03	41.575386	6.5182
3ls4.67	0.125	1	850.565	3783.5002	3.7835002	6.82	47.022245	8.3795
3ls5.25	0.134	1	819.3089	3644.4662	3.6444662	6.12	42.195915	7.6114
3ls5.25	0.127	1	748.7214	3330.4775	3.3304775	5.91	40.748016	6.0924
3ls5.25	0.124	1	800.7263	3561.8067	3.5618067	6.43	44.333289	7.4354
3ls5.25	0.126	1	716.6438	3187.7893	3.1877893	5.69	39.231169	6.1289
3ls5.25	0.128	1	780.9799	3473.9704	3.4739704	6.08	41.920124	6.8347
3ls5.67	0.13	1	793.2154	3528.3966	3.5283966	6.09	41.989072	6.7604
3ls5.67	0.13	1	776.6564	3454.7385	3.4547385	5.96	41.092753	7.1372
3ls5.67	0.128	1	810.5473	3605.4927	3.6054927	6.35	43.781709	7.1902
3ls5.67	0.131	1	765.5525	3405.3459	3.4053459	5.83	40.196435	6.6444
3ls5.67	0.136	1	806.5569	3587.7425	3.5877425	5.93	40.885911	7.2576
3ls6.25	0.137	1	779.4175	3467.0205	3.4670205	5.7	39.300117	8.0107
3ls6.25	0.135	1	768.9468	3420.4445	3.4204445	5.7	39.300117	7.1823
3ls6.25	0.142	1	783.1117	3483.4531	3.4834531	5.52	38.05906	7.239
3ls6.25	0.143	1	900.4605	4005.4464	4.0054464	6.28	43.299076	8.326
3ls6.25	0.138	1	790.0439	3514.2891	3.5142891	5.71	39.369064	6.9903
4ld4.67	0.168	1	1031.659	4589.0462	4.5890462	6.15	42.402757	6.8737
4ld4.67	0.162	1	1029.4858	4579.3793	4.5793793	6.37	43.919604	7.3411

4ld4.67	0.16	1	1149.6159	5113.7444	5.1137444	7.19	49.573305	8.9576
4ld4.67	0.157	1	1054.1088	4688.9078	4.6889078	6.72	46.332769	7.2265
4ld4.67	0.176	1	960.8088	4273.8889	4.2738889	5.47	37.714322	7.5275
4ld5.25	0.17	1	1061.3959	4721.3225	4.7213225	6.26	43.161181	8.6679
4ld5.25	0.161	1	985.7804	4384.9681	4.3849681	6.12	42.195915	7.3613
4ld5.25	0.155	1	1077.9954	4795.1607	4.7951607	6.96	47.987511	8.2367
4ld5.25	0.169	1	1052.7218	4682.7382	4.6827382	6.22	42.88539	7.2346
4ld5.25	0.165	1	997.1562	4435.5702	4.4355702	6.05	41.713282	8.1586
4ld5.67	0.172	1	993.3412	4418.6002	4.4186002	5.77	39.78275	7.6945
4ld5.67	0.166	1	1122.3019	4992.2458	4.9922458	6.78	46.746454	7.5626
4ld5.67	0.158	1	1002.661	4460.0567	4.4600567	6.36	43.850656	6.4875
4ld5.67	0.165	1	1102.655	4904.852	4.904852	6.67	45.988031	7.5624
4ld5.67	0.184	1	1059.1382	4711.2797	4.7112797	5.76	39.713802	6.7373
4ld6.25	0.161	1	1059.6745	4713.6653	4.7136653	6.59	45.436451	7.7346
4ld6.25	0.157	1	1129.0772	5022.3838	5.0223838	7.19	49.573305	7.5732
4ld6.25	0.153	1	1085.7946	4829.8533	4.8298533	7.11	49.021724	6.7406
4ld6.25	0.165	1	1052.6911	4682.6016	4.6826016	6.37	43.919604	7.1841
4ld6.25	0.17	1	1054.7488	4691.7547	4.6917547	6.21	42.816443	8.1691
4ls4.67	0.149	1	853.6113	3797.0509	3.7970509	5.73	39.506959	7.1453
4ls4.67	0.152	1	995.733	4429.2394	4.4292394	6.54	45.091713	7.8692
4ls4.67	0.15	1	811.8684	3611.3693	3.6113693	5.43	37.438532	6.6582
4ls4.67	0.149	1	799.359	3555.7247	3.5557247	5.38	37.093794	7.5653
4ls4.67	0.148	1	919.1547	4088.6023	4.0886023	6.21	42.816443	8.1917
4ls5.25	0.151	1	1006.0157	4474.9792	4.4749792	6.68	46.056979	8.2936
4ls5.25	0.157	1	1063.362	4730.0681	4.7300681	6.78	46.746454	8.3313
4ls5.25	0.159	1	1018.7876	4531.7914	4.5317914	6.42	44.264342	7.5885
4ls5.25	0.16	1	977.6379	4348.7485	4.3487485	6.12	42.195915	8.0873
4ls5.25	0.161	1	878.5392	3907.9356	3.9079356	5.46	37.645375	7.4802
4ls5.67	0.158	1	874.0397	3887.9209	3.8879209	5.55	38.265903	8.7821
4ls5.67	0.162	1	929.8348	4136.1098	4.1361098	5.73	39.506959	9.0114
4ls5.67	0.156	1	863.8426	3842.5619	3.8425619	5.55	38.265903	7.2624
4ls5.67	0.154	1	884.1792	3933.0236	3.9330236	5.72	39.438012	8.2082
4ls5.67	0.144	1	899.8383	4002.6787	4.0026787	6.25	43.092233	9.5261
4ls6.25	0.159	1	907.2765	4035.7655	4.0357655	5.72	39.438012	8.8257
4ls6.25	0.163	1	988.2524	4395.9641	4.3959641	6.05	41.713282	8.626
4ls6.25	0.152	1	887.2403	3946.64	3.94664	5.85	40.33433	9.1126
4ls6.25	0.157	1	969.1035	4310.7856	4.3107856	6.16	42.471705	9.6088
4ls6.25	0.157	1	970.174	4315.5474	4.3155474	6.17	42.540652	9.1154

Table B.2 Raw data for x-direction tensile test

	Thickness (in)	Width (in)	Maximum Load (lbf)	Max Load (N)	Max Load (kN)	Stress@ Max (ksi)	Max stress (Mpa)	Tensile strain at Maximum Load (%)
2ld4.67	0.105	1	489.1984	2176.0621	2.1760621	4.64	31.991674	4.8261
2ld4.67	0.102	1	479.5967	2133.3516	2.1333516	4.71	32.474307	5.0372
2ld4.67	0.105	1	440.668	1960.1882	1.9601882	4.2	28.957981	4.3883
2ld4.67	0.106	1	468.643	2084.6272	2.0846272	4.4	30.336932	4.9396
2ld4.67	0.106	1	447.4949	1990.5558	1.9905558	4.2	28.957981	3.7306
2ld5.25	0.105	1	502.4814	2235.1478	2.2351478	4.79	33.025887	4.5623
2ld5.25	0.104	1	523.208	2327.3443	2.3273443	5.03	34.680629	5.0664
2ld5.25	0.104	1	516.7445	2298.5932	2.2985932	4.95	34.129049	5.0002
2ld5.25	0.104	1	510.2749	2269.815	2.269815	4.89	33.715363	4.1678
2ld5.25	0.104	1	481.2998	2140.9274	2.1409274	4.61	31.784831	3.6043
2ld5.67	0.101	1	403.3687	1794.2727	1.7942727	3.98	27.441134	4.8357
2ld5.67	0.101	1	427.6415	1902.2435	1.9022435	4.22	29.095876	5.3328
2ld5.67	0.105	1	411.602	1830.8962	1.8308962	3.93	27.096396	5.9843
2ld5.67	0.101	1	419.5864	1866.4126	1.8664126	4.14	28.544295	5.9502
2ld5.67	0.1	1	438.2799	1949.5654	1.9495654	4.39	30.267985	5.6361
2ld6.25	0.111	1	593.3774	2639.4732	2.6394732	5.33	36.749056	6.5361
2ld6.25	0.111	1	496.6439	2209.1813	2.2091813	4.49	30.95746	5.4001
2ld6.25	0.115	1	555.044	2468.9578	2.4689578	4.84	33.370625	5.545
2ld6.25	0.111	1	564.155	2509.4856	2.5094856	5.08	35.025367	5.7046
2ld6.25	0.111	1	572.6539	2547.2905	2.5472905	5.16	35.576948	5.8906
2ls4.67	0.092	1	591.5	2631.1221	2.6311221	6.43	44.333289	7.6193
2ls4.67	0.093	1	589.3056	2621.361	2.621361	6.33	43.643814	8.0078
2ls4.67	0.092	1	571.0982	2540.3704	2.5403704	6.2	42.747495	6.7302
2ls4.67	0.093	1	559.3429	2488.0803	2.4880803	6.01	41.437491	6.9139
2ls4.67	0.094	1	568.0528	2526.8238	2.5268238	6.06	41.782229	6.9302
2ls5.25	0.099	1	611.514	2720.1488	2.7201488	6.17	42.540652	6.7551
2ls5.25	0.098	1	647.9616	2882.2757	2.8822757	6.61	45.574346	6.6577
2ls5.25	0.095	1	649.8378	2890.6215	2.8906215	6.84	47.16014	6.7531
2ls5.25	0.097	1	627.3709	2790.6838	2.7906838	6.45	44.471185	6.6655
2ls5.25	0.098	1	594.9413	2646.4298	2.6464298	6.09	41.989072	6.0139
2ls5.67	0.106	1	643.749	2863.5372	2.8635372	6.06	41.782229	6.8065
2ls5.67	0.106	1	641.1479	2851.9669	2.8519669	6.07	41.851177	5.9872
2ls5.67	0.107	1	661.9491	2944.4952	2.9444952	6.16	42.471705	6.9893
2ls5.67	0.104	1	649.47	2888.9854	2.8889854	6.24	43.023286	6.6882
2ls5.67	0.104	1	662.4515	2946.73	2.94673	6.36	43.850656	6.8884
2ls6.25	0.118	1	596.3651	2652.7632	2.6527632	5.04	34.749577	7.1085
2ls6.25	0.11	1	603.2534	2683.4038	2.6834038	5.47	37.714322	6.8702
2ls6.25	0.112	1	655.4929	2915.7766	2.9157766	5.87	40.472225	7.1287
2ls6.25	0.114	1	633.8647	2819.5696	2.8195696	5.57	38.403798	7.1605

2ls6.25	0.109	1	601.6575	2676.3049	2.6763049	5.51	37.990113	7.1365
3ld4.67	0.146	1	457.8852	2036.7741	2.0367741	3.13	21.58059	7.3177
3ld4.67	0.152	1	394.1555	1753.2904	1.7532904	2.59	17.857421	5.3862
3ld4.67	0.148	1	456.8733	2032.273	2.032273	3.09	21.3048	6.4975
3ld4.67	0.149	1	440.763	1960.6108	1.9606108	2.95	20.339534	6.4037
3ld4.67	0.149	1	447.5226	1990.679	1.990679	3	20.684272	6.8134
3ld5.25	0.13	1	688.9553	3064.6247	3.0646247	5.3	36.542214	5.9853
3ld5.25	0.127	1	661.463	2942.3329	2.9423329	5.19	35.78379	5.9162
3ld5.25	0.134	1	607.2236	2701.0642	2.7010642	4.53	31.233251	4.9079
3ld5.25	0.128	1	637.3315	2834.9907	2.8349907	4.96	34.197996	5.6308
3ld5.25	0.129	1	694.8297	3090.7554	3.0907554	5.39	37.162742	6.2826
3ld5.67	0.135	1	740.5295	3294.0381	3.2940381	5.49	37.852218	7.3085
3ld5.67	0.134	1	717.0197	3189.4614	3.1894614	5.36	36.955899	6.1418
3ld5.67	0.134	1	724.3955	3222.2706	3.2222706	5.39	37.162742	6.3308
3ld5.67	0.134	1	738.1798	3283.5861	3.2835861	5.5	37.921165	5.4026
3ld5.67	0	0	0	0	0	0	0	0
3ld6.25	0.14	1	757.453	3369.3176	3.3693176	5.43	37.438532	5.9105
3ld6.25	0.138	1	709.0329	3153.9343	3.1539343	5.13	35.370105	5.6893
3ld6.25	0.143	1	746.9149	3322.4418	3.3224418	5.21	35.921685	6.0333
3ld6.25	0.141	1	701.2054	3119.1159	3.1191159	4.99	34.404839	5.2867
3ld6.25	0.142	1	709.2635	3154.9601	3.1549601	4.98	34.335891	6.2376
3ls4.67	0.12	1	692.9635	3082.4541	3.0824541	5.77	39.78275	6.7067
3ls4.67	0.123	1	622.3901	2768.5281	2.7685281	5.05	34.818524	5.8441
3ls4.67	0.119	1	677.799	3014.9991	3.0149991	5.72	39.438012	6.4708
3ls4.67	0.125	1	662.7582	2948.0943	2.9480943	5.3	36.542214	6.095
3ls4.67	0.12	1	703.0674	3127.3985	3.1273985	5.84	40.265383	7.1832
3ls5.25	0.126	1	894.0096	3976.7514	3.9767514	7.09	48.883829	7.2028
3ls5.25	0.124	1	887.6714	3948.5577	3.9485577	7.14	49.228567	7.7496
3ls5.25	0.124	1	881.8805	3922.7985	3.9227985	7.13	49.159619	7.1712
3ls5.25	0.124	1	874.6111	3890.4626	3.8904626	7.06	48.676986	7.6345
3ls5.25	0.124	1	822.767	3659.8486	3.6598486	6.66	45.919084	6.82
3ls5.67	0.129	1	770.7318	3428.3846	3.4283846	6	41.368544	6.5346
3ls5.67	0.126	1	697.1416	3101.0392	3.1010392	5.53	38.128008	6.6409
3ls5.67	0.133	1	712.2893	3168.4195	3.1684195	5.34	36.818004	4.5757
3ls5.67	0.134	1	808.685	3597.2088	3.5972088	6.02	41.506439	5.7412
3ls5.67	0.124	1	842.6398	3748.2472	3.7482472	6.77	46.677507	6.7705
3ls6.25	0.137	1	871.1558	3875.0927	3.8750927	6.34	43.712761	5.8071
3ls6.25	0.139	1	829.2831	3688.8337	3.6888337	5.99	41.299596	6.2172
3ls6.25	0.139	1	738.1917	3283.6391	3.2836391	5.31	36.611161	6.4924
3ls6.25	0.14	1	868.5302	3863.4134	3.8634134	6.23	42.954338	6.4797
3ls6.25	0.137	1	857.6988	3815.233	3.815233	6.25	43.092233	6.2208
4ld4.67	0.167	1	878.2766	3906.7675	3.9067675	5.27	36.335371	8.0739
4ld4.67	0.162	1	950.8125	4229.4232	4.2294232	5.85	40.33433	7.7216
4ld4.67	0.163	1	840.6172	3739.2502	3.7392502	5.17	35.645895	6.4499
4ld4.67	0.164	1	934.7391	4157.9252	4.1579252	5.69	39.231169	7.7049
4ld4.67	0.165	1	963.8481	4287.4084	4.2874084	5.84	40.265383	8.6024

4ld5.25	0.169	1	869.5802	3868.084	3.868084	5.15	35.508	8.6073
4ld5.25	0.164	1	809.338	3600.1135	3.6001135	4.94	34.060101	7.4393
4ld5.25	0.165	1	862.1962	3835.2384	3.8352384	5.24	36.128528	8.0864
4ld5.25	0.168	1	807.6467	3592.5902	3.5925902	4.81	33.163783	7.3055
4ld5.25	0.164	1	812.0396	3612.1308	3.6121308	4.95	34.129049	7.4762
4ld5.67	0.173	1	818.2919	3639.9424	3.6399424	4.73	32.612202	6.8863
4ld5.67	0.172	1	859.3967	3822.7856	3.8227856	5.01	34.542734	7.2831
4ld5.67	0.169	1	850.2036	3781.8927	3.7818927	5.03	34.680629	7.0713
4ld5.67	0.175	1	848.5718	3774.6341	3.7746341	4.84	33.370625	7.2703
4ld5.67	0.174	1	875.4544	3894.2138	3.8942138	5.02	34.611682	7.0208
4ld6.25	0.162	1	935.8383	4162.8146	4.1628146	5.79	39.920645	8.0801
4ld6.25	0.162	1	903.8856	4020.682	4.020682	5.6	38.610641	7.676
4ld6.25	0.159	1	776.9172	3455.8986	3.4558986	4.9	33.784311	6.4578
4ld6.25	0.164	1	830.5021	3694.2561	3.6942561	5.06	34.887472	6.8689
4ld6.25	0.159	1	833.3252	3706.8138	3.7068138	5.24	36.128528	6.5724
4ls4.67	0.14	1	931.5634	4143.7989	4.1437989	6.67	45.988031	8.2423
4ls4.67	0.144	1	975.0377	4337.1822	4.3371822	6.77	46.677507	7.8582
4ls4.67	0.146	1	991.171	4408.9467	4.4089467	6.79	46.815402	8.363
4ls4.67	0.148	1	989.1576	4399.9906	4.3999906	6.71	46.263821	8.5476
4ls4.67	0.144	1	961.686	4277.7909	4.2777909	6.66	45.919084	8.0412
4ls5.25	0.15	1	759.3587	3377.7946	3.3777946	5.07	34.956419	7.7245
4ls5.25	0.154	1	724.5685	3223.0401	3.2230401	4.7	32.405359	7.0453
4ls5.25	0.158	1	806.2753	3586.4899	3.5864899	5.1	35.163262	7.8753
4ls5.25	0.148	1	786.1622	3497.0224	3.4970224	5.31	36.611161	8.0728
4ls5.25	0.151	1	801.2527	3564.1483	3.5641483	5.29	36.473266	6.9168
4ls5.67	0.156	1	933.2188	4151.1625	4.1511625	6	41.368544	7.6637
4ls5.67	0.16	1	940.9931	4185.7443	4.1857443	5.88	40.541173	8.4083
4ls5.67	0.155	1	952.0128	4234.7624	4.2347624	6.13	42.264862	8.9994
4ls5.67	0.156	1	976.4988	4343.6815	4.3436815	6.25	43.092233	8.0108
4ls5.67	0.156	1	996.325	4431.8728	4.4318728	6.37	43.919604	8.1089
4ls6.25	0.174	1	1024.9595	4559.2453	4.5592453	5.89	40.61012	7.4899
4ls6.25	0.168	1	912.305	4058.1333	4.0581333	5.44	37.50748	8.2502
4ls6.25	0.164	1	980.4018	4361.0429	4.3610429	5.99	41.299596	8.9494
4ls6.25	0.166	1	956.5947	4255.1437	4.2551437	5.75	39.644854	8.0877
4ls6.25	0.171	1	970.2088	4315.7022	4.3157022	5.68	39.162221	8.1421

Table B.3 Raw data for y-direction flex testing

	Width (in)	Depth (in)	Span (in)	Load @ Max (lbf)	Max Load (N)	Max Load (kN)	Flexure stress at Load @ Max (ksi)	Max flex stress (Mpa)	Young's Modulus (Automatic Limit) (Mpsi)
2ld4.67	1.008	0.099	1.63	45.47	202.26056	0.2022606	11.251	77.5729143	0.396
2ld4.67	1.007	0.101	1.63	42.35	188.38212	0.1883821	10.002	68.9613624	0.431
2ld4.67	1.009	0.102	1.63	43.26	192.43	0.19243	10.102	69.6508382	0.443
2ld4.67	1.009	0.102	1.63	44.54	198.12372	0.1981237	10.425	71.8778448	0.48
2ld4.67	1.01	0.105	1.63	37.81	168.1872	0.1681872	8.267	56.9989585	0.393
2ld5.25	1.008	0.106	1.67	49.7	221.07653	0.2210765	10.915	75.2562759	0.476
2ld5.25	1.007	0.105	1.67	49.21	218.89691	0.2188969	11.206	77.2626502	0.477
2ld5.25	1.009	0.107	1.67	52.25	232.4195	0.2324195	11.332	78.1313896	0.526
2ld5.25	1.009	0.1	1.67	38.26	170.1889	0.1701889	9.466	65.2657725	0.531
2ld5.25	1.01	0.104	1.67	53.59	238.38011	0.2383801	12.267	84.5779877	0.543
2ld5.67	1.008	0.102	1.63	33.59	149.41571	0.1494157	7.769	53.5653694	0.364
2ld5.67	1.007	0.103	1.63	33.1	147.23608	0.1472361	7.633	52.6276824	0.382
2ld5.67	1.009	0.099	1.63	34.86	155.06495	0.1550649	8.581	59.1639123	0.376
2ld5.67	1.009	0.1	1.63	29.78	132.46799	0.132468	7.231	49.85599	0.35
2ld5.67	1.01	0.105	1.63	38.29	170.32234	0.1703223	8.355	57.6056972	0.385
2ld6.25	1.008	0.109	1.79	42.45	188.82694	0.1888269	9.522	65.6518789	0.546
2ld6.25	1.007	0.113	1.79	45.05	200.39231	0.2003923	9.463	65.2450883	0.537
2ld6.25	1.009	0.112	1.79	31.73	141.14202	0.141142	6.721	46.3396638	0.396
2ld6.25	1.009	0.111	1.79	41.61	185.09043	0.1850904	8.951	61.7149725	0.527
2ld6.25	1.01	0.114	1.79	40.08	178.28466	0.1782847	8.171	56.3370618	0.471
2ls4.67	1.008	0.091	1.48	47.78	212.53595	0.212536	12.781	88.121893	0.487
2ls4.67	1.007	0.093	1.48	46.76	207.99877	0.2079988	11.836	81.6063473	0.462
2ls4.67	1.009	0.093	1.48	50.78	225.88061	0.2258806	13.001	89.6387396	0.503
2ls4.67	1.009	0.094	1.48	51.52	229.17229	0.2291723	12.797	88.2322091	0.502
2ls4.67	1.01	0.092	1.48	42.03	186.95869	0.1869587	10.833	74.6909058	0.427
2ls5.25	1.008	0.092	1.52	51.02	226.94818	0.2269482	13.556	93.4653299	0.567
2ls5.25	1.007	0.095	1.52	46.89	208.57704	0.208577	11.775	81.1857671	0.535
2ls5.25	1.009	0.094	1.52	54.19	241.04904	0.241049	13.75	94.8029128	0.561
2ls5.25	1.009	0.096	1.52	55.07	244.96348	0.2449635	13.434	92.6241695	0.479
2ls5.25	1.01	0.097	1.52	57.82	257.19608	0.2571961	13.864	95.5889151	0.512
2ls5.67	1.008	0.1	1.65	43.64	194.12032	0.1941203	10.724	73.9393772	0.451
2ls5.67	1.007	0.104	1.65	54.8	243.76246	0.2437625	12.358	85.2054106	0.459
2ls5.67	1.009	0.104	1.65	51.96	231.12951	0.2311295	11.713	80.7582922	0.524
2ls5.67	1.009	0.102	1.65	41.09	182.77736	0.1827774	9.785	67.4652001	0.443
2ls5.67	1.01	0.106	1.65	55.53	247.00966	0.2470097	12.198	84.1022495	0.499
2ls6.25	1.008	0.109	1.72	59.04	262.62291	0.2626229	12.645	87.184206	0.504
2ls6.25	1.007	0.106	1.72	51.23	227.88231	0.2278823	11.712	80.7513974	0.5
2ls6.25	1.009	0.109	1.72	56.93	253.23716	0.2532372	12.244	84.4194083	0.552

2ls6.25	1.009	0.106	1.72	46.17	205.37432	0.2053743	10.554	72.7672685	0.505
2ls6.25	1.01	0.108	1.72	51.38	228.54954	0.2285495	11.243	77.5177562	0.479
3ld4.67	1.008	0.131	2.27	46.7	207.73187	0.2077319	9.163	63.1766611	0.465
3ld4.67	1.007	0.146	2.27	37.26	165.74068	0.1657407	5.891	40.6170152	0.297
3ld4.67	1.009	0.15	2.27	37.59	167.20859	0.1672086	5.679	39.1553267	0.319
3ld4.67	1.009	0.148	2.27	40.74	181.22048	0.1812205	6.273	43.2508125	0.296
3ld4.67	1.01	0.135	2.27	42.13	187.40351	0.1874035	7.786	53.6825803	0.417
3ld5.25	1.008	0.125	2.01	66.49	295.76215	0.2957621	12.8	88.2528934	0.637
3ld5.25	1.007	0.127	2.01	60.55	269.33972	0.2693397	11.304	77.9383364	0.563
3ld5.25	1.009	0.125	2.01	61.91	275.3893	0.2753893	11.818	81.4822417	0.544
3ld5.25	1.009	0.128	2.01	63.99	284.6416	0.2846416	11.773	81.1719776	0.569
3ld5.25	1.01	0.125	2.01	68.36	304.08032	0.3040803	13.067	90.0937935	0.595
3ld5.67	1.008	0.129	2.16	74.19	330.01344	0.3300134	14.384	99.1741889	0.613
3ld5.67	1.007	0.133	2.16	72.71	323.43008	0.3234301	13.124	90.4867947	0.616
3ld5.67	1.009	0.138	2.16	75.65	336.50784	0.3365078	12.823	88.4114728	0.593
3ld5.67	1.009	0.138	2.16	64.94	288.86741	0.2888674	10.867	74.9253275	0.488
3ld5.67	1.01	0.136	2.16	64.95	288.91189	0.2889119	11.243	77.5177562	0.441
3ld6.25	1.008	0.144	2.27	65.69	292.20357	0.2922036	10.667	73.546376	0.56
3ld6.25	1.007	0.143	2.27	76.37	339.71056	0.3397106	12.656	87.2600483	0.629
3ld6.25	1.009	0.141	2.27	63.95	284.46367	0.2844637	10.839	74.7322743	0.6
3ld6.25	1.009	0.138	2.27	56.3	250.43479	0.2504348	10.007	68.9958362	0.503
3ld6.25	1.01	0.143	2.27	68.52	304.79203	0.304792	11.32	78.0486526	0.622
3ls4.67	1.008	0.126	1.96	53.59	238.38011	0.2383801	9.797	67.5479372	0.441
3ls4.67	1.007	0.121	1.96	55.93	248.78894	0.2487889	11.206	77.2626502	0.517
3ls4.67	1.009	0.123	1.96	56.87	252.97027	0.2529703	10.948	75.4838028	0.493
3ls4.67	1.009	0.122	1.96	60.43	268.80593	0.2688059	11.771	81.1581881	0.52
3ls4.67	1.01	0.12	1.96	63.05	280.46027	0.2804603	12.697	87.5427333	0.555
3ls5.25	1.008	0.126	2	69.23	307.95027	0.3079503	12.937	89.1974751	0.52
3ls5.25	1.007	0.125	2	64.3	286.02055	0.2860205	12.231	84.3297765	0.568
3ls5.25	1.009	0.123	2	72.13	320.85011	0.3208501	14.115	97.3194992	0.508
3ls5.25	1.009	0.123	2	71.88	319.73805	0.3197381	14.093	97.1678145	0.538
3ls5.25	1.01	0.126	2	63.66	283.17369	0.2831737	11.794	81.3167675	0.46
3ls5.67	1.008	0.13	2.08	65.68	292.15909	0.2921591	11.971	82.5371396	0.482
3ls5.67	1.007	0.13	2.08	56.54	251.50236	0.2515024	10.26	70.7402098	0.467
3ls5.67	1.009	0.126	2.08	65.54	291.53634	0.2915363	12.688	87.4806805	0.55
3ls5.67	1.009	0.13	2.08	71.32	317.24705	0.3172471	12.936	89.1905803	0.529
3ls5.67	1.01	0.131	2.08	63.66	283.17369	0.2831737	11.4	78.6002331	0.484
3ls6.25	1.008	0.148	2.34	59.28	263.69048	0.2636905	9.368	64.5900863	0.418
3ls6.25	1.007	0.151	2.34	56.47	251.19098	0.251191	8.679	59.8395985	0.375
3ls6.25	1.009	0.143	2.34	63.2	281.1275	0.2811275	10.758	74.173799	0.482
3ls6.25	1.009	0.144	2.34	63.65	283.1292	0.2831292	10.605	73.1189011	0.433
3ls6.25	1.01	0.145	2.34	61.05	271.56383	0.2715638	10.132	69.8576809	0.416
4ld4.67	1.008	0.17	2.71	70.45	313.3771	0.3133771	9.866	68.0236755	0.548
4ld4.67	1.007	0.173	2.71	65.15	289.80153	0.2898015	8.786	60.5773376	0.488
4ld4.67	1.009	0.17	2.71	69.75	310.26335	0.3102633	9.773	67.382463	0.535
4ld4.67	1.009	0.169	2.71	67.67	301.01105	0.301011	9.543	65.7966688	0.523

4ld4.67	1.01	0.165	2.71	66.98	297.94178	0.2979418	9.876	68.092623	0.518
4ld5.25	1.008	0.167	2.69	73.91	328.76794	0.3287679	10.628	73.2774805	0.546
4ld5.25	1.007	0.167	2.69	61.69	274.41069	0.2744107	8.85	61.018602	0.499
4ld5.25	1.009	0.172	2.69	80.92	359.94996	0.35995	10.968	75.621698	0.508
4ld5.25	1.009	0.173	2.69	71.86	319.64909	0.3196491	9.644	66.4930393	0.489
4ld5.25	1.01	0.162	2.69	77.22	343.49155	0.3434915	11.708	80.7238184	0.531
4ld5.67	1.008	0.161	2.74	73.64	327.56692	0.3275669	11.617	80.0963955	0.623
4ld5.67	1.007	0.176	2.74	84.47	375.74114	0.3757411	11.159	76.9385966	0.472
4ld5.67	1.009	0.17	2.74	76.24	339.13229	0.3391323	10.78	74.3254836	0.51
4ld5.67	1.009	0.17	2.74	83.57	371.73775	0.3717377	11.816	81.4684522	0.516
4ld5.67	1.01	0.181	2.74	91.81	408.39108	0.4083911	11.4	78.6002331	0.492
4ld6.25	1.008	0.158	2.59	67.85	301.81173	0.3018117	10.52	72.5328467	0.479
4ld6.25	1.007	0.167	2.59	77.39	344.24775	0.3442477	10.755	74.1531147	0.499
4ld6.25	1.009	0.166	2.59	78.13	347.53943	0.3475394	10.914	75.2493811	0.491
4ld6.25	1.009	0.159	2.59	73.85	328.50105	0.328501	11.223	77.3798611	0.482
4ld6.25	1.01	0.16	2.59	76.44	340.02194	0.3400219	11.452	78.9587605	0.527
4ls4.67	1.008	0.148	2.34	72.73	323.51904	0.323519	11.494	79.2483403	0.478
4ls4.67	1.007	0.151	2.34	62.02	275.8786	0.2758786	9.532	65.7208265	0.415
4ls4.67	1.009	0.143	2.34	49.47	220.05344	0.2200534	8.422	58.0676459	0.403
4ls4.67	1.009	0.144	2.34	54.02	240.29284	0.2402928	9.001	62.0597104	0.387
4ls4.67	1.01	0.145	2.34	71.97	320.13839	0.3201384	11.943	82.3440864	0.507
4ls5.25	1.008	0.152	2.43	49.59	220.58723	0.2205872	7.735	53.3309477	0.339
4ls5.25	1.007	0.149	2.43	76.94	342.24605	0.342246	12.615	86.9773633	0.562
4ls5.25	1.009	0.15	2.43	54.15	240.87111	0.2408711	8.753	60.3498106	0.431
4ls5.25	1.009	0.155	2.43	79.35	352.96626	0.3529663	11.928	82.240665	0.485
4ls5.25	1.01	0.155	2.43	68.81	306.08202	0.306082	10.365	71.4641593	0.45
4ls5.67	1.008	0.155	2.56	61.55	273.78794	0.2737879	9.803	67.5893057	0.509
4ls5.67	1.007	0.156	2.56	64.67	287.66639	0.2876664	10.111	69.712891	0.457
4ls5.67	1.009	0.16	2.56	62.25	276.9017	0.2769017	9.204	63.4593461	0.407
4ls5.67	1.009	0.167	2.56	59.3	263.77945	0.2637794	8.056	55.5441648	0.322
4ls5.67	1.01	0.161	2.56	57.72	256.75126	0.2567513	8.5	58.605437	0.437
4ls6.25	1.008	0.163	2.6	46.35	206.175	0.206175	6.787	46.7947177	0.399
4ls6.25	1.007	0.163	2.6	46.62	207.37602	0.207376	6.773	46.6981911	0.418
4ls6.25	1.009	0.161	2.6	51.02	226.94818	0.2269482	7.615	52.5035768	0.467
4ls6.25	1.009	0.164	2.6	52.41	233.13121	0.2331312	7.576	52.2346813	0.452
4ls6.25	1.01	0.163	2.6	55.61	247.36551	0.2473655	8.125	56.019903	0.473

Table B.4 Raw data for x-direction flex test

	Width (in)	Depth (in)	Span (in)	Load @ Max (lbf)	Max Load (N)	Max Load (kN)	Flexure stress at Load @ Max (ksi)	Max flex stress (Mpa)	Young's Modulus (Automatic Limit) (Mpsi)
2ld4.67	1.005	0.107	1.66	44.77	199.14681	0.1991468	9.69	66.8101982	0.507
2ld4.67	1.008	0.104	1.66	45.14	200.79265	0.2007927	10.388	71.6227388	0.521
2ld4.67	1.005	0.101	1.66	45.51	202.43849	0.2024385	11.133	76.7593329	0.569
2ld4.67	1.006	0.103	1.66	42.39	188.56005	0.18856	9.888	68.1753601	0.464
2ld4.67	1	0.248	4	36.68	163.16071	0.1631607	3.578	24.6694416	0.47
2ld5.25	1.02	0.105	1.71	47.01	209.11082	0.2091108	10.676	73.6084289	0.493
2ld5.25	1.009	0.105	1.71	44	195.72168	0.1957217	10.153	70.0024708	0.503
2ld5.25	1.012	0.107	1.71	50.73	225.6582	0.2256582	11.298	77.8969679	0.473
2ld5.25	1.009	0.11	1.71	50.83	226.10302	0.226103	10.623	73.2430067	0.473
2ld5.25	1.008	0.106	1.71	42.91	190.87312	0.1908731	9.635	66.4309865	0.513
2ld5.67	1.013	0.103	1.66	41.37	184.02286	0.1840229	9.64	66.4654603	0.433
2ld5.67	1.008	0.105	1.66	43.07	191.58484	0.1915848	9.714	66.9756723	0.401
2ld5.67	1.011	0.103	1.66	40.56	180.4198	0.1804198	9.512	65.5829314	0.462
2ld5.67	1.011	0.105	1.66	40.57	180.46429	0.1804643	9.084	62.6319752	0.402
2ld5.67	1.012	0.104	1.66	33.26	147.9478	0.1479478	7.533	51.9382067	0.344
2ld6.25	1.013	0.111	1.77	45.21	201.10403	0.201104	9.65	66.5344079	0.449
2ld6.25	1.016	0.107	1.77	48.17	214.27076	0.2142708	10.927	75.3390129	0.483
2ld6.25	1.011	0.108	1.77	54.03	240.33733	0.2403373	12.149	83.7644064	0.576
2ld6.25	1.007	0.114	1.77	49.86	221.78825	0.2217882	10.093	69.5887854	0.469
2ld6.25	1.007	0.112	1.77	48.22	214.49317	0.2144932	10.084	69.5267325	0.422
2ls4.67	1.006	0.09	1.48	48.79	217.02865	0.2170287	13.304	91.727851	0.591
2ls4.67	1.007	0.092	1.48	39.98	177.83984	0.1778398	10.453	72.070898	0.502
2ls4.67	1.006	0.091	1.48	41.48	184.51217	0.1845122	11.003	75.8630145	0.514
2ls4.67	1.036	0.097	1.48	49.22	218.94139	0.2189414	11.261	77.6418619	0.493
2ls4.67	1.004	0.092	1.48	39.22	174.45919	0.1744592	10.245	70.6367885	0.491
2ls5.25	1.024	0.097	1.52	46.8	208.1767	0.2081767	11.165	76.9799652	0.506
2ls5.25	1.006	0.094	1.52	44.03	195.85513	0.1958551	11.284	77.8004413	0.558
2ls5.25	1.004	0.096	1.52	36.52	162.44899	0.162449	9.1	62.7422914	0.532
2ls5.25	1.005	0.098	1.52	48.47	215.60522	0.2156052	11.574	79.7999209	0.569
2ls5.25	1.006	0.092	1.52	43.67	194.25377	0.1942538	11.704	80.6962394	0.575
2ls5.67	1.003	0.103	1.66	44.99	200.12542	0.2001254	10.591	73.0223745	0.603
2ls5.67	1.008	0.099	1.66	43.43	193.18619	0.1931862	10.865	74.911538	0.61
2ls5.67	1.009	0.102	1.66	45.87	204.03985	0.2040399	10.762	74.201378	0.555
2ls5.67	1.006	0.099	1.66	37.44	166.54136	0.1665414	9.528	65.6932475	0.631
2ls5.67	0.991	0.115	1.66	36.51	162.40451	0.1624045	6.898	47.5600358	0.316
2ls6.25	1.008	0.109	1.72	46.7	207.73187	0.2077319	4.555	31.4056195	0.544
2ls6.25	1.007	0.106	1.72	34.5	153.46359	0.1534636	3.365	23.2008583	0.433
2ls6.25	1.009	0.109	1.72	31.33	139.36273	0.1393627	3.057	21.077273	0.409

2ls6.25	1.009	0.106	1.72	36.7	163.24967	0.1632497	3.58	24.6832311	0.511
2ls6.25	1.01	0.108	1.72	36.59	162.76037	0.1627604	3.569	24.6073888	0.52
3ld4.67	1.009	0.139	2.31	63.7	283.35161	0.2833516	11.36	78.3244428	0.546
3ld4.67	1.009	0.138	2.31	67.47	300.1214	0.3001214	12.187	84.0264071	0.525
3ld4.67	1.019	0.152	2.31	42.05	187.04765	0.1870477	6.198	42.7337057	0.222
3ld4.67	1.016	0.149	2.31	42.44	188.78246	0.1887825	6.558	45.2158183	0.336
3ld4.67	1.011	0.145	2.31	60.3	268.22767	0.2682277	9.793	67.5203582	0.4
3ld5.25	1.016	0.132	2.1	53.8	239.31424	0.2393142	9.594	66.1483015	0.508
3ld5.25	1.014	0.13	2.1	64.31	286.06503	0.286065	11.858	81.758032	0.475
3ld5.25	1.018	0.133	2.1	51.32	228.28265	0.2282827	9.018	62.1769213	0.503
3ld5.25	1.01	0.129	2.1	50.73	225.6582	0.2256582	9.536	65.7484055	0.474
3ld5.25	1.019	0.134	2.1	65.4	290.91359	0.2909136	11.348	78.2417058	0.509
3ld5.67	1.007	0.142	2.22	40.44	179.88602	0.179886	6.603	45.5260824	0.343
3ld5.67	1.008	0.137	2.22	64.49	286.86571	0.2868657	11.421	78.745023	0.497
3ld5.67	1.008	0.137	2.22	57.41	255.37231	0.2553723	10.075	69.4646797	0.418
3ld5.67	1.009	0.139	2.22	46	204.61812	0.2046181	7.922	54.6202673	0.331
3ld5.67	1.013	0.14	2.22	74.45	331.16998	0.33117	12.504	86.2120452	0.614
3ld6.25	1.013	0.14	2.27	64.48	286.82123	0.2868212	11.022	75.9940149	0.544
3ld6.25	1.014	0.145	2.27	55.12	245.18589	0.2451859	8.807	60.7221275	0.471
3ld6.25	1.014	0.141	2.27	82.12	365.28783	0.3652878	13.902	95.8509159	0.714
3ld6.25	1.014	0.145	2.27	61.84	275.07792	0.2750779	9.86	67.9823069	0.49
3ld6.25	1.013	0.139	2.27	58.19	258.84192	0.2588419	10.159	70.0438393	0.522
3ls4.67	1.007	0.123	1.97	82.76	368.13469	0.3681347	16.174	111.515804	0.991
3ls4.67	1.01	0.124	1.97	75.53	335.97406	0.3359741	14.336	98.8432406	0.837
3ls4.67	1.005	0.125	1.97	68.88	306.39339	0.3063934	13.002	89.6456343	0.731
3ls4.67	1.007	0.124	1.97	74.95	333.39409	0.3333941	14.265	98.3537128	0.818
3ls4.67	1.005	0.121	1.97	53.92	239.84802	0.239848	10.923	75.3114339	0.548
3ls5.25	1.018	0.123	1.97	68.48	304.61411	0.3046141	13.206	91.0521648	0.603
3ls5.25	1.008	0.122	1.97	58.34	259.50915	0.2595092	11.514	79.3862355	0.617
3ls5.25	1.008	0.127	1.97	64.71	287.84432	0.2878443	11.834	81.5925578	0.53
3ls5.25	1.008	0.118	1.97	59.25	263.55704	0.263557	12.44	85.7707807	0.599
3ls5.25	1.008	0.126	1.97	66.52	295.89559	0.2958956	12.244	84.4194083	0.529
3ls5.67	1.006	0.128	2.09	63.95	284.46367	0.2844637	12.294	84.7641462	0.605
3ls5.67	1.01	0.133	2.09	61.44	273.29864	0.2732986	10.868	74.9322223	0.526
3ls5.67	1.009	0.132	2.09	54.97	244.51865	0.2445187	9.806	67.60999	0.54
3ls5.67	1.004	0.131	2.09	61.71	274.49966	0.2744997	11.198	77.2074922	0.56
3ls5.67	1.006	0.131	2.09	56.3	250.43479	0.2504348	10.232	70.5471566	0.51
3ls6.25	1.009	0.138	2.16	49.78	221.43239	0.2214324	8.403	57.9366455	0.452
3ls6.25	1.008	0.133	2.16	55.05	244.87451	0.2448745	10.025	69.1199419	0.488
3ls6.25	1.009	0.133	2.16	53.84	239.49216	0.2394922	9.796	67.5410424	0.533
3ls6.25	1.008	0.135	2.16	63.27	281.43888	0.2814389	11.098	76.5180164	0.516
3ls6.25	1.006	0.136	2.16	55	244.6521	0.2446521	9.519	65.6311947	0.463
4ld4.67	1.013	0.166	2.69	87.9	390.99854	0.3909985	12.678	87.411733	0.619
4ld4.67	1.014	0.168	2.69	67.37	299.67658	0.2996766	9.466	65.2657725	0.535
4ld4.67	1.014	0.173	2.69	72.26	321.42838	0.3214284	9.602	66.2034595	0.459
4ld4.67	1.014	0.169	2.69	69.24	307.99475	0.3079948	9.644	66.4930393	0.515

4ld4.67	1.013	0.164	2.69	71.13	316.40189	0.3164019	10.586	72.9879007	0.535
4ld5.25	1.013	0.169	2.71	68.52	304.79203	0.304792	9.639	66.4585655	0.5
4ld5.25	1.014	0.171	2.71	82.27	365.95506	0.3659551	11.268	77.6901252	0.541
4ld5.25	1.014	0.168	2.71	86.32	383.97035	0.3839704	12.267	84.5779877	0.608
4ld5.25	1.014	0.173	2.71	85.4	379.87799	0.379878	11.45	78.944971	0.553
4ld5.25	1.013	0.167	2.71	72.28	321.51734	0.3215173	10.461	72.126056	0.561
4ld5.67	1.009	0.176	2.82	83.18	370.00294	0.3700029	11.324	78.0762316	0.558
4ld5.67	1.01	0.176	2.82	74.68	332.19307	0.3321931	10.082	69.512943	0.489
4ld5.67	1.009	0.177	2.82	86.95	386.77273	0.3867727	11.647	80.3032382	0.533
4ld5.67	1.014	0.172	2.82	64.63	287.48846	0.2874885	9.163	63.1766611	0.488
4ld5.67	1.016	0.182	2.82	86.81	386.14998	0.38615	10.968	75.621698	0.488
4ld6.25	1.009	0.167	2.67	86.6	385.21585	0.3852159	12.322	84.9571994	0.591
4ld6.25	1.012	0.169	2.67	72.31	321.65079	0.3216508	9.965	68.7062564	0.411
4ld6.25	1.013	0.162	2.67	68.93	306.6158	0.3066158	10.392	71.6503178	0.478
4ld6.25	1.011	0.172	2.67	74.55	331.6148	0.3316148	9.981	68.8165725	0.363
4ld6.25	1.021	0.164	2.67	72.88	324.18627	0.3241863	10.679	73.6291131	0.505
4ls4.67	1.006	0.149	2.33	60.38	268.58352	0.2685835	9.463	65.2450883	0.448
4ls4.67	1.006	0.144	2.33	75.73	336.8637	0.3368637	12.643	87.1704165	0.492
4ls4.67	1.005	0.149	2.33	73.07	325.03144	0.3250314	11.524	79.455183	0.55
4ls4.67	1.006	0.141	2.33	74.35	330.72516	0.3307252	12.986	89.5353182	0.503
4ls4.67	1.005	0.146	2.33	76.47	340.15538	0.3401554	12.447	85.819044	0.575
4ls5.25	1.01	0.153	2.41	52.8	234.86602	0.234866	8.051	55.509691	0.411
4ls5.25	1.014	0.149	2.41	50.07	222.72238	0.2227224	8.089	55.7716917	0.432
4ls5.25	1.009	0.153	2.41	51.83	230.55124	0.2305512	7.945	54.7788467	0.435
4ls5.25	1.012	0.148	2.41	57.93	257.68538	0.2576854	9.423	64.969298	0.399
4ls5.25	1.01	0.151	2.41	52.39	233.04225	0.2330422	8.223	56.6955892	0.425
4ls5.67	1.007	0.155	2.47	49.89	221.9217	0.2219217	7.636	52.6483667	0.398
4ls5.67	1.005	0.151	2.47	47.86	212.89181	0.2128918	7.699	53.0827364	0.428
4ls5.67	1.009	0.157	2.47	54.16	240.9156	0.2409156	8.112	55.9302712	0.46
4ls5.67	1.006	0.152	2.47	57.34	255.06093	0.2550609	9.085	62.63887	0.437
4ls5.67	1.01	0.157	2.47	59.02	262.53394	0.2625339	8.816	60.7841803	0.484
4ls6.25	1.011	0.164	2.61	53.46	237.80184	0.2378018	7.659	52.8069461	0.403
4ls6.25	1.015	0.16	2.61	55.44	246.60932	0.2466093	8.385	57.8125399	0.411
4ls6.25	1.012	0.161	2.61	58.85	261.77775	0.2617777	8.797	60.6531799	0.438
4ls6.25	1.021	0.167	2.61	69.32	308.35061	0.3083506	9.488	65.4174572	0.493
4ls6.25	1.016	0.162	2.61	56.14	249.72307	0.2497231	8.179	56.3922199	0.392

Table B.5 Raw data for impact testing

Preform Construction	Impact Energy (J)	Impact Velocity (m/sec)	Max Load (N)	Max Load (kN)	Energy to Max Load (J)	Time to Max Load (msec)	Deflection at Max Load (mm)	Total Energy (J)
2ld4.67	107.25	4.29	791.50	0.79	3.36	1.67	7.16	6.12
2ld4.67	105.76	4.26	796.90	0.80	2.51	1.37	5.82	6.03
2ld4.67	107.71	4.30	829.60	0.83	2.16	1.10	4.72	6.30
2ld4.67	109.97	4.35	859.00	0.86	5.05	1.98	8.56	9.42
2ld4.67								
Mean	107.67	4.30	819.25	0.82	3.27	1.53	6.57	6.97
Standard Deviation	1.74	0.03	31.39	0.03	1.29	0.38	1.67	1.64
Coefficient of Variation	0.02	0.01	0.04	0.04	0.39	0.25	0.25	0.23
2ld5.25	108.77	4.32	874.10	0.87	3.75	1.56	6.73	5.68
2ld5.25	106.61	4.28	835.30	0.84	2.37	1.25	5.35	5.78
2ld5.25	108.42	4.32	933.90	0.93	3.31	1.37	5.88	5.16
2ld5.25	109.52	4.34	879.20	0.88	3.11	1.45	6.27	7.34
2ld5.25	109.02	4.33	775.00	0.78	2.53	1.36	5.87	4.88
Mean	108.47	4.32	859.50	0.86	3.01	1.40	6.02	5.77
Standard Deviation	1.11	0.02	58.87	0.06	0.57	0.12	0.52	0.95
Coefficient of Variation	0.01	0.01	0.07	0.07	0.19	0.08	0.09	0.17
2ld5.67	109.86	4.34	743.10	0.74	3.67	1.78	7.71	8.07
2ld5.67	106.12	4.27	703.70	0.70	2.55	1.52	6.47	5.52
2ld5.67	108.51	4.36	701.20	0.70	2.60	1.35	5.83	4.55
2ld5.67	110.33	4.35	766.10	0.77	3.69	1.77	7.68	6.17
2ld5.67								
Mean	108.70	4.33	728.53	0.73	3.13	1.60	6.92	6.08
Standard Deviation	1.89	0.04	31.56	0.03	0.64	0.21	0.93	1.49
Coefficient of Variation	0.02	0.01	0.04	0.04	0.20	0.13	0.13	0.24
2ld6.25	107.78	4.30	1128.50	1.13	3.50	1.11	4.76	9.72
2ld6.25	110.69	4.36	820.20	0.82	2.57	1.23	5.35	5.91
2ld6.25	107.40	4.30	904.20	0.90	3.91	1.63	6.96	9.41
2ld6.25	107.10	4.29	936.10	0.94	3.58	1.60	6.83	6.59
2ld6.25	109.81	4.34	989.40	0.99	2.87	1.25	5.41	6.09
Mean	108.56	4.32	955.68	0.96	3.29	1.36	5.86	7.54
Standard	1.59	0.03	114.45	0.11	0.55	0.23	0.98	1.87

Deviation								
Coefficient of Variation	0.01	0.01	0.12	0.12	0.17	0.17	0.17	0.25
2ls4.67	106.13	4.27	684.60	0.68	2.29	1.42	6.05	5.04
2ls4.67	108.87	4.32	735.60	0.74	2.15	1.33	5.75	6.20
2ls4.67	107.62	4.30	671.70	0.67	2.73	1.70	7.32	4.30
2ls4.67	109.72	4.34	680.00	0.68	2.15	1.28	5.54	4.75
2ls4.67	109.58	4.34	715.90	0.72	2.52	1.47	6.38	4.52
Mean	108.38	4.32	697.56	0.70	2.37	1.44	6.21	4.96
Standard Deviation	1.51	0.03	27.06	0.03	0.25	0.17	0.70	0.74
Coefficient of Variation	0.01	0.01	0.04	0.04	0.11	0.12	0.11	0.15
2ls5.25	106.88	4.29	684.90	0.68	2.32	1.41	6.02	5.38
2ls5.25	109.85	4.34	766.40	0.77	3.78	1.80	7.81	5.35
2ls5.25	108.42	4.32	861.50	0.86	2.84	1.44	6.22	5.63
2ls5.25	110.89	4.36	784.30	0.78	2.04	1.25	5.44	5.04
2ls5.25	109.89	4.33	790.40	0.79	2.31	1.35	5.83	5.52
Mean	109.19	4.33	777.50	0.78	2.66	1.45	6.26	5.38
Standard Deviation	1.56	0.03	63.18	0.06	0.69	0.21	0.91	0.22
Coefficient of Variation	0.01	0.01	0.08	0.08	0.26	0.15	0.15	0.04
2ls5.67	108.87	4.32	874.50	0.87	3.28	1.58	6.83	5.16
2ls5.67	107.92	4.31	895.90	0.90	3.38	1.54	6.63	5.20
2ls5.67	108.03	4.31	946.80	0.95	3.99	1.63	6.97	5.40
2ls5.67	107.53	4.30	869.40	0.87	3.74	1.66	7.11	6.12
2ls5.67	109.47	4.34	848.80	0.85	2.94	1.44	6.24	5.59
Mean	108.36	4.31	887.08	0.89	3.47	1.57	6.75	5.49
Standard Deviation	0.79	0.02	37.35	0.04	0.41	0.08	0.34	0.39
Coefficient of Variation	0.01	0.00	0.04	0.04	0.12	0.05	0.05	0.07
2ls6.25	107.16	4.29	773.20	0.77	2.50	1.14	4.88	6.61
2ls6.25	109.38	4.33	778.20	0.78	3.44	1.60	6.90	5.28
2ls6.25	110.81	4.36	867.60	0.87	2.94	1.21	5.27	6.00
2ls6.25	109.24	4.33	858.20	0.86	3.70	1.53	6.61	7.15
2ls6.25	109.22	4.33	794.00	0.79	2.38	1.26	5.46	5.23
Mean	109.16	4.33	814.24	0.81	2.99	1.35	5.82	6.05
Standard Deviation	1.30	0.03	45.20	0.05	0.57	0.20	0.88	0.84
Coefficient of Variation	0.01	0.01	0.06	0.06	0.19	0.15	0.15	0.14
3ld4.67	109.89	4.44	1096.30	1.10	4.83	1.55	6.68	9.82
3ld4.67	109.60	4.34	1080.00	1.08	3.37	1.20	5.17	11.50

3ld4.67	107.00	4.29	1059.90	1.06	3.88	1.31	5.58	9.14
3ld4.67	107.94	4.31	1088.80	1.09	3.92	1.28	5.48	8.33
3ld4.67	107.08	4.29	1233.00	1.23	5.82	1.75	7.45	10.01
Mean	108.30	4.33	1111.60	1.11	4.36	1.41	6.07	9.76
Standard Deviation	1.37	0.06	69.22	0.07	0.97	0.23	0.96	1.18
Coefficient of Variation	0.01	0.01	0.06	0.06	0.22	0.16	0.16	0.12
3ld5.25	108.66	4.32	1400.90	1.40	5.58	1.62	6.97	7.83
3ld5.25	109.48	4.34	1249.20	1.25	4.50	1.44	6.23	7.81
3ld5.25	108.94	4.33	1213.70	1.21	3.82	1.19	5.11	9.14
3ld5.25	108.96	4.33	1169.50	1.17	3.84	1.35	5.81	9.27
3ld5.25								
Mean	109.01	4.33	1258.33	1.26	4.44	1.40	6.03	8.51
Standard Deviation	0.34	0.01	100.49	0.10	0.83	0.18	0.78	0.80
Coefficient of Variation	0.00	0.00	0.08	0.08	0.19	0.13	0.13	0.09
3ld5.67	109.13	4.33	1225.60	1.23	5.15	1.56	6.73	12.38
3ld5.67	106.33	4.27	1431.60	1.43	6.08	1.59	6.73	12.07
3ld5.67	107.99	4.31	1407.30	1.41	6.51	1.74	7.41	10.44
3ld5.67	106.63	4.28	1325.90	1.33	6.65	1.93	8.20	11.51
3ld5.67	107.48	4.30	1111.20	1.11	4.96	1.65	7.06	9.44
Mean	107.51	4.30	1300.32	1.30	5.87	1.69	7.22	11.17
Standard Deviation	1.12	0.02	132.93	0.13	0.77	0.15	0.61	1.22
Coefficient of Variation	0.01	0.01	0.10	0.10	0.13	0.09	0.09	0.11
3ld6.25	109.73	4.34	1346.50	1.35	5.20	1.54	6.65	9.42
3ld6.25	107.73	4.30	1545.00	1.55	5.98	1.57	6.71	9.53
3ld6.25	106.65	4.28	1436.20	1.44	5.30	1.51	6.40	11.51
3ld6.25	106.44	4.28	1505.00	1.51	6.90	1.65	6.97	9.88
3ld6.25	109.61	4.34	1493.40	1.49	6.11	1.60	6.89	11.53
Mean	108.03	4.31	1465.22	1.47	5.90	1.57	6.73	10.38
Standard Deviation	1.57	0.03	76.94	0.08	0.69	0.05	0.22	1.06
Coefficient of Variation	0.01	0.01	0.05	0.05	0.12	0.03	0.03	0.10
3ls4.67	108.75	4.32	1124.40	1.12	5.01	1.73	7.42	9.70
3ls4.67	107.34	4.29	1092.00	1.09	4.94	1.74	7.41	9.06
3ls4.67	108.25	4.31	1077.60	1.08	5.39	1.77	7.59	7.98
3ls4.67	109.76	4.34	1175.50	1.18	5.41	1.75	7.56	9.86
3ls4.67	107.82	4.30	1039.20	1.04	3.69	1.45	6.20	8.44
Mean	108.38	4.32	1101.74	1.10	4.89	1.69	7.24	9.01

Standard Deviation	0.93	0.02	51.34	0.05	0.70	0.14	0.59	0.80
Coefficient of Variation	0.01	0.00	0.05	0.05	0.14	0.08	0.08	0.09
3ls5.25	107.54	4.30	1172.10	1.17	4.73	1.53	6.48	8.94
3ls5.25	108.79	4.32	1244.30	1.24	5.35	1.70	7.29	10.31
3ls5.25	108.37	4.32	1201.80	1.20	5.18	1.59	6.82	10.98
3ls5.25	110.04	4.35	1347.70	1.35	5.31	1.60	6.90	11.90
3ls5.25	110.61	4.36	1242.60	1.24	6.01	1.81	7.84	8.72
Mean	109.07	4.33	1241.70	1.24	5.32	1.65	7.07	10.17
Standard Deviation	1.24	0.02	66.48	0.07	0.46	0.11	0.52	1.35
Coefficient of Variation	0.01	0.01	0.05	0.05	0.09	0.07	0.07	0.13
3ls5.67	108.64	4.32	1368.90	1.37	5.95	1.71	7.32	8.10
3ls5.67	110.28	4.35	1317.50	1.32	6.03	1.74	7.51	11.74
3ls5.67	109.45	4.34	1233.00	1.23	4.78	1.54	6.65	10.00
3ls5.67	110.39	4.36	1270.50	1.27	5.00	1.53	6.62	8.39
3ls5.67	107.03	4.29	1354.80	1.35	5.92	1.66	7.07	10.31
Mean	109.16	4.33	1308.94	1.31	5.53	1.64	7.04	9.71
Standard Deviation	1.39	0.03	57.04	0.06	0.60	0.10	0.40	1.49
Coefficient of Variation	0.01	0.01	0.04	0.04	0.11	0.06	0.06	0.15
3ls6.25	107.32	4.29	1488.30	1.49	7.78	1.94	8.26	10.40
3ls6.25	110.25	4.35	1449.50	1.45	5.85	1.59	6.88	10.74
3ls6.25	107.49	4.30	1324.40	1.32	4.47	1.37	5.86	9.58
3ls6.25	107.70	4.30	1335.70	1.34	6.21	1.73	7.40	11.17
3ls6.25	107.68	4.30	1190.50	1.19	7.39	1.99	8.49	11.18
Mean	108.09	4.31	1357.68	1.36	6.34	1.73	7.38	10.61
Standard Deviation	1.22	0.02	117.29	0.12	1.31	0.26	1.07	0.66
Coefficient of Variation	0.01	0.01	0.09	0.09	0.21	0.15	0.14	0.06
4ld4.67	108.27	4.31	1821.30	1.82	7.27	1.43	6.09	14.83
4ld4.67	107.14	4.29	1922.50	1.92	9.48	1.77	7.49	13.61
4ld4.67	108.84	4.32	1790.60	1.79	7.40	1.55	6.64	15.05
4ld4.67	106.46	4.28	1769.40	1.77	8.39	1.76	7.41	16.01
4ld4.67	107.21	4.29	1955.10	1.96	8.46	1.64	6.96	14.89
Mean	107.58	4.30	1851.78	1.85	8.20	1.63	6.92	14.88
Standard Deviation	0.96	0.02	82.36	0.08	0.90	0.14	0.58	0.85
Coefficient of Variation	0.01	0.00	0.04	0.04	0.11	0.09	0.08	0.06
4ld5.25	109.11	4.33	2120.80	2.12	10.03	1.71	7.28	15.09

4ld5.25	110.31	4.35	2077.80	2.08	10.44	1.83	7.84	18.90
4ld5.25	108.22	4.31	2091.50	2.09	9.78	1.74	7.40	14.93
4ld5.25	107.36	4.29	2122.70	2.12	11.68	1.87	7.87	15.90
4ld5.25	108.61	4.32	2015.70	2.02	7.50	1.34	5.75	11.47
Mean	108.72	4.32	2085.70	2.09	9.89	1.70	7.23	15.26
Standard Deviation	1.09	0.02	43.58	0.04	1.52	0.21	0.87	2.65
Coefficient of Variation	0.01	0.01	0.02	0.02	0.15	0.12	0.12	0.17
4ld5.67	107.02	4.29	2229.30	2.23	10.50	1.71	7.23	16.90
4ld5.67	108.45	4.32	1973.60	1.97	8.45	1.59	6.77	12.92
4ld5.67	108.82	4.32	1709.00	1.71	11.17	2.15	9.14	16.71
4ld5.67	109.84	4.34	1558.00	1.56	7.84	1.52	6.51	13.71
4ld5.67	110.33	4.35	1749.80	1.75	5.74	1.17	5.04	15.65
Mean	108.89	4.33	1843.94	1.84	8.74	1.63	6.94	15.18
Standard Deviation	1.29	0.03	261.80	0.26	2.17	0.36	1.48	1.79
Coefficient of Variation	0.01	0.01	0.14	0.14	0.25	0.22	0.21	0.12
4ld6.25	107.37	4.29	1075.10	1.08	8.79	1.67	7.08	11.96
4ld6.25	106.00	4.27	1904.40	1.90	8.81	1.76	7.41	14.02
4ld6.25	110.19	4.35	1597.40	1.60	6.91	1.57	6.79	11.94
4ld6.25	110.74	4.36	2070.40	2.07	8.86	1.66	7.16	13.45
4ld6.25	106.92	4.29	1835.00	1.84	8.14	1.66	7.03	12.64
Mean	108.24	4.31	1696.46	1.70	8.30	1.67	7.09	12.80
Standard Deviation	2.10	0.04	386.71	0.39	0.83	0.07	0.22	0.92
Coefficient of Variation	0.02	0.01	0.23	0.23	0.10	0.04	0.03	0.07
4ls4.67	109.80	4.34	1656.20	1.66	7.68	1.73	7.44	12.46
4ls4.67	110.32	4.28	1608.10	1.61	7.71	1.83	7.76	13.28
4ls4.67	108.75	4.35	1645.40	1.65	6.90	1.67	7.21	11.89
4ls4.67	107.34	4.29	1338.70	1.34	6.34	1.73	7.35	10.86
4ls4.67	109.60	4.34	1570.80	1.57	6.95	1.71	7.35	10.62
Mean	109.16	4.32	1563.84	1.56	7.12	1.73	7.42	11.82
Standard Deviation	1.16	0.03	130.27	0.13	0.58	0.06	0.21	1.11
Coefficient of Variation	0.01	0.01	0.08	0.08	0.08	0.03	0.03	0.09
4ls5.25	108.15	4.31	1247.50	1.25	6.31	1.78	7.62	11.57
4ls5.25	108.65	4.32	1597.40	1.60	7.16	1.81	7.74	13.53
4ls5.25	109.47	4.34	1393.20	1.39	7.12	1.86	7.74	13.01
4ls5.25	109.10	4.33	1619.60	1.62	8.42	1.87	7.98	14.69
4ls5.25	106.91	4.29	1836.20	1.84	8.19	1.75	7.39	12.37

Mean	108.45	4.32	1538.78	1.54	7.44	1.81	7.69	13.03
Standard Deviation	0.99	0.02	226.09	0.23	0.86	0.05	0.21	1.18
Coefficient of Variation	0.01	0.00	0.15	0.15	0.12	0.03	0.03	0.09
4ls5.67	108.90	4.33	1393.20	1.39	6.77	1.72	7.36	13.93
4ls5.67	109.84	4.34	1477.80	1.48	6.47	1.71	7.36	15.07
4ls5.67	109.38	4.34	1457.80	1.46	7.03	1.71	7.36	16.39
4ls5.67	108.83	4.32	1516.00	1.52	6.33	1.66	7.12	14.94
4ls5.67	107.62	4.30	1470.40	1.47	7.76	1.91	8.12	14.67
Mean	108.91	4.33	1463.04	1.46	6.87	1.74	7.46	15.00
Standard Deviation	0.83	0.02	44.67	0.04	0.57	0.10	0.38	0.89
Coefficient of Variation	0.01	0.00	0.03	0.03	0.08	0.06	0.05	0.06
4ls6.25	109.07	4.33	1621.00	1.62	6.54	1.49	6.38	18.53
4ls6.25	106.95	4.29	1700.90	1.70	8.85	1.93	8.15	15.37
4ls6.25	107.71	4.30	1638.10	1.64	6.94	1.62	6.92	13.66
4ls6.25	107.33	4.29	1461.00	1.46	5.91	1.53	6.54	15.53
4ls6.25	109.19	4.33	1714.50	1.71	7.19	1.63	7.01	16.72
Mean	108.05	4.31	1627.10	1.63	7.08	1.64	7.00	15.96
Standard Deviation	1.02	0.02	101.04	0.10	1.10	0.17	0.69	1.81
Coefficient of Variation	0.01	0.00	0.06	0.06	0.15	0.10	0.10	0.11

Table B.6 Raw data for fiberglass y-direction tensile

Preform Construction	Thickness (mm)	Width (mm)	Maximum Load (N)	Mas Stress (Mpa)	Tensile strain at Maximum Load (%)	Modulus (Chord 0.025 % - 0.5 %) (GPa)
4L0.79	27.43	254.0	34466	496.42	8.402	3.774
4L2	28.96	254.0	46745	636.39	9.180	4.549
4L2	24.38	254.0	50679	813.58	10.071	5.480
4L2	30.73	254.0	51305	657.76	10.137	4.196
Mean .	27.88	254.00	45799	651.04	9.45	4.50
Standard Deviation	2.69	0.00	7820	129.85	0.82	0.73
Coefficient of Variation	0.10	0.00	0	0.20	0.09	0.16
4L1.38	32.51	254.0	47829	579.85	9.192	3.810
4L3.5	32.00	254.0	42056	518.49	8.092	4.043
4L3.5	32.00	254.0	49168	606.05	9.361	4.045

4L3.5	33.02	254.0	42891	512.97	8.357	3.975
Mean .	32.39	254.00	45486	554.34	8.75	3.97
Standard Deviation	0.49	0.00	3538	45.90	0.62	0.11
Coefficient of Variation	0.02	0.00	0	0.08	0.07	0.03
4L1.97	32.77	254.0	51245	616.39	10.142	3.768
4L5	33.53	254.0	55614	653.62	10.483	3.990
4L5	33.53	355.6	46613	389.55	9.199	2.734
4L5	33.27	355.6	52724	446.78	10.243	2.801
Mean .	33.27	304.80	51549	526.59	10.02	3.32
Standard Deviation	0.36	58.66	3757	128.26	0.56	0.65
Coefficient of Variation	0.01	0.19	0	0.24	0.06	0.20

Table B.7 Raw data for fiberglass x-direction tensile

Preform Construction	Thickness (mm)	Width (mm)	Max Load (N)	Stress at Max (Mpa)	Tensile strain at Maximum Load (%)	Modulus (Chord 0.025 % - 0.5 %) (GPa)
4L2	29.21	254.0	13350	180.0	6.166	2.359
4L2	20.57	254.0	9169	176.5	5.586	1.722
4L2	21.59	254.0	10957	199.9	5.617	2.207
4L2	30.48	254.0	15327	197.9	6.786	2.014
Mean .	25.46	254.0	12201	188.6	6.04	2.08
Standard Deviation	5.10	0.0	2697	12.1	0.57	0.27
Coefficient of Variation	0.20	0.0	0	0.1	0.09	0.13
4L3.5	30.23	254.0	22179	288.9	7.569	2.171
4L3.5	34.29	254.0	24199	277.2	7.149	2.258
4L3.5	33.27	254.0	22885	271.7	7.324	2.389
4L3.5	33.53	254.0	18425	216.5	6.483	1.990
Mean .	32.83	254.0	21922	263.6	7.13	2.20
Standard Deviation	1.79	0.0	2477	32.2	0.47	0.17
Coefficient of Variation	0.05	0.0	0	0.1	0.07	0.08
4L5	33.02	254.0	26433	316.5	7.034	2.799
4L5	33.78	254.0	29291	339.9	7.962	2.642

4L5	33.78	254.0	29155	338.5	7.817	2.667
4L5	34.04	254.0	27009	311.0	7.151	2.719
Mean .	33.66	254.0	27972	326.5	7.49	2.71
Standard Deviation	0.44	0.0	1465	14.9	0.47	0.07
Coefficient of Variation	0.01	0.0	0	0.0	0.06	0.03

Table B.8 Raw data for fiberglass y-direction flex

Preform Construction	Width (mm)	Depth (mm)	Span (mm)	Load @ Max (N)	Flexure Stress at Max Load (Mpa)	Young's Modulus (Automatic Limit) (Mpsi)
4L2	355.6	28.45	454.7	2942	700.9	2.825
4L2	355.6	30.23	454.7	3092	652.9	2.520
4L2	355.6	26.92	454.7	2663	700.0	3.021
4L2	355.6	28.19	454.7	2466	599.2	2.688
Mean	355.6	28.45	454.7	2791	663.3	2.764
Standard Deviation	0.0	1.36	0.0	280	48.2	0.212
Coefficient of Variation	0.0	0.05	0.0	0	0.1	0.077
4L3.5	355.6	30.48	513.1	3006	700.3	2.713
4L3.5	355.6	32.26	513.1	3084	644.1	2.392
4L3.5	355.6	33.53	513.1	2748	533.9	1.949
4L3.5	355.6	32.26	513.1	2558	529.5	1.907
Mean	355.6	32.13	513.1	2849	601.9	2.240
Standard Deviation	0.0	1.25	0.0	242	84.3	0.384
Coefficient of Variation	0.0	0.04	0.0	0	0.1	0.171
4L5	355.6	37.85	607.1	2443	433.8	1.773
4L5	355.6	38.10	607.1	2691	475.6	2.174
4L5	355.6	38.86	607.1	2885	485.7	1.897
4L5	355.6	36.58	607.1	2782	532.6	2.551
Mean	355.6	37.85	607.1	2700	481.9	2.099
Standard Deviation	0.0	0.95	0.0	189	40.6	0.345
Coefficient of Variation	0.0	0.03	0.0	0	0.1	0.164

Table B.9 Raw data for fiberglass x-direction flex

Preform Construction	Width (mm)	Depth (mm)	Span (mm)	Load @ Max (N)	Flexure Stress at Max Load (Mpa)	Young's Modulus (Automatic Limit) (Mpsi)
4L2	355.6	26.92	442.0	1195	309.7	1.850
4L2	355.6	22.61	442.0	688	250.1	1.683
4L2	355.6	30.73	442.0	1359	266.7	1.614
4L2	355.6	30.23	442.0	1342	273.4	1.584
Mean	355.6	27.62	442.0	1146	275.0	1.683
Standard Deviation	0.0	3.75	0.0	314	25.1	0.119
Coefficient of Variation	0.0	0.14	0.0	0	0.1	0.071
4L3.5	355.6	32.26	505.5	1520	309.9	1.688
4L3.5	355.6	31.75	505.5	1777	377.5	2.099
4L3.5	355.6	30.99	505.5	1681	374.8	1.998
4L3.5	355.6	31.50	505.5	1724	370.4	1.855
Mean	355.6	31.62	505.5	1675	358.1	1.910
Standard Deviation	0.0	0.53	0.0	111	32.3	0.179
Coefficient of Variation	0.0	0.02	0.0	0	0.1	0.094
4L5	355.6	33.53	523.2	1920	376.7	2.067
4L5	355.6	33.27	523.2	2134	424.8	2.191
4L5	355.6	32.26	523.2	2097	445.4	2.599
4L5	355.6	32.00	523.2	2152	467.4	2.457
Mean	355.6	32.77	523.2	2076	428.6	2.329
Standard Deviation	0.0	0.75	0.0	106	38.7	0.243
Coefficient of Variation	0.0	0.02	0.0	0	0.1	0.104