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Novel Interlaminar Reinforcement To Enhance The Impact Damage Resistance Of Carbon Fiber-Reinforced Polymer Matrix Composites

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NOVEL INTERLAMINAR REINFORCEMENT TO ENHANCE THE IMPACT DAMAGE RESISTANCE OF CARBON FIBER-REINFORCED POLYMER MATRIX COMPOSITES

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Dedication

This thesis is dedicated to my sweet and beautiful daughter. She is one of main the reasons why I continued to further my education. I want to give her the best example as her mother, as a role model, and as a human being. I want to dedicate this hard work to my loving husband because he has been with me since day one supporting and motivating me to finish this goal in life.

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by

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THESIS

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Thank you, everyone!

Abstract

Aerospace, aircraft, marine, and automobile applications are increasingly using composite materials for lighter, higher stiffness, and strength properties. Despite these advantages, composite materials have one major disadvantage. The through-thickness properties are extremely weak when subjected to impact damage. When a composite material is subjected to a low-velocity impact, there is hardly any visible damage on the surface compromising the composite material internally without any external notice. Internal damage may be delamination, which is the most common, matrix cracking, and fiber breakage. A composite material is made up of layers of fiber. The interlaminar region is located in between these layers. This region is a resin-rich area that has extremely poor mechanical properties due to no reinforcement.

The arrest of delamination is essential for composite materials when they are used for impact applications. Delamination reduces the laminates' strength and stiffness, making the composite unsafe and limiting its full potential when impacted. The interlaminar region may be modified in the fiber (3D) or in the matrix (2D). An example of 3D interlaminar reinforcement is stitching and Z-pinning which increases the through-thickness mechanical properties by penetrating through the layers of fiber. For 2D interlaminar reinforcement, nanotubes and nanowires are used to strengthen the interlaminar region without perforating the layers. These modifications have proven to increase the through-thickness mechanical properties. However, it has been shown to damage or breaks the fibers. 3D interlaminar reinforcement has also been revealed to decrease the in-plane properties of a composite material. To strengthen the through-thickness mechanical properties without sacrificing the other orientation's mechanical properties, Aramid pulp or Kevlar has been introduced as an interlaminar reinforcement. The main purpose of this research is to determine the ideal amount of Aramid pulp that is necessary to reinforce the interlaminar

region of a carbon fiber-reinforced polymer (CFRP) composite during a low-velocity impact scenario. Three different groups of Aramid pulp to resin ratio were studied, one times reinforcement (1X), two times reinforcement (2X), and four times reinforcement (4X).
After analysis, 1X is the recommended Aramid pulp-to-resin ratio, 1:15 in volume.
2X reinforcement consisted of a 2:15 by volume of Aramid pulp to resin ratio and 4X reinforcement 4:15 ratio. Data such as energy, time, displacement, and contact force were obtained and examined using the Instron CEAST 9340 for drop weight impact testing. The impacted energy used for this research was 5 Joules (J) following the standard for ASTM D7136/D7136M-20. The outcome of this investigation recorded 1X is the ideal quantity of reinforcement for a CFRP composite. A laminate that used more than 1X reinforcement exhibit a higher degree of damage, greater deformation, lower maximum force, lower impact duration, and brittle-like properties. 2X and 4X reinforcement laminates showed an increase in air pockets during manufacturing leading to a decrease in bending stiffness [1].

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Chapter 1: Introduction

INTRODUCTION TO COMPOSITES

Composite materials are composed of two or more constituent materials. Each material possesses different mechanical properties, when put together, the composite material's performance and properties combine the properties of the two constituents' materials. Composite materials consist of two phases, reinforcement and matrix, shown in Figure 1.1. Reinforcement is mostly discontinuous and has stiffer and stronger properties. Reinforcement can be made up of particulate (e.g., cement) or fiber reinforcement (e.g., carbon fiber and aramid). A matrix is a continuous and weaker phase, meaning lower mechanical properties. A matrix can be made up of ceramic, metal, or polymer. This combination allows composite materials to have lightweight and have a high-strength-to-weight ratio and high-stiffness-to-weight ratio.

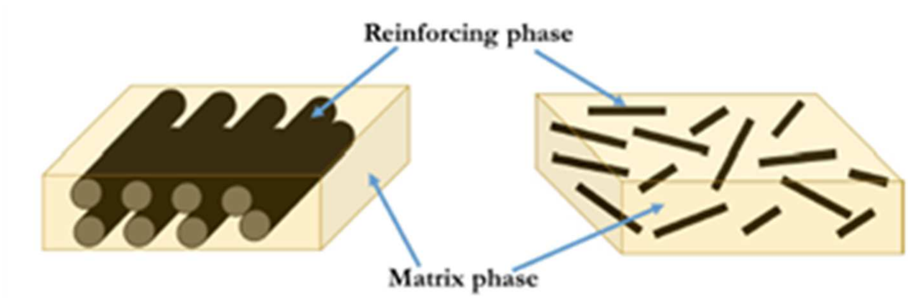


Figure 1.1: Phases of a composite from [2]

REINFORCEMENTS

There are three types of reinforcement, particulate, fiber, and structural. Particulate reinforcement, also known as particulate composites, can be described as a regular (isotropic) or irregular structure. Particulate composites have two phases, the particulates, and the matrix. Particulates provide excellent material properties and the matrix will be the binding medium for structural applications. A good example would be concrete. Cement is the matrix and sand and gravel, are the particulates [3]. There are two types of particulate reinforcements, flake and skeletal (Figure 1.2). A flake composite will contain flat reinforcements of a matrix. Examples of flake composites are glass, aluminum, and silver. Skeletal composites are continuous skeletal matrices that are filled with a second material, such as a honeycomb [3].

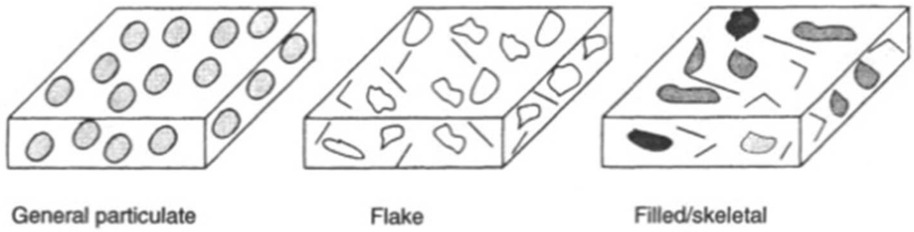


Figure 1.2: Types of particulate reinforcement from [4]

Fiber reinforcement can be classified as woven fabric, discontinuous, and continuous, as shown in Figure 1.3. Discontinuous is considered to be short /chopped fiber reinforcement. Continuous is long and unidirectional and woven fabric is bidirectional fiber reinforcement. An example is woven carbon fiber [4].

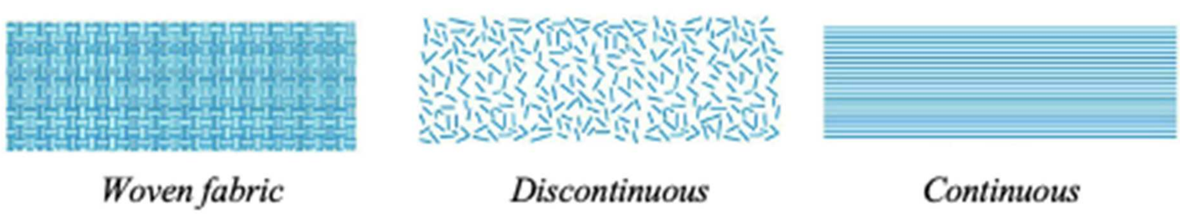


Figure 1.3: Types of fiber reinforcement from [4]

Structural composites can be classified as laminar or sandwich structures. Laminar consists of plies or lamina. Laminates may be stacked up and arranged in desired orientations for higher strength. The sandwich composites are also layered; however, it consists of two faces and a core. Its stiffness is increased due to its structure of faces being the outer layers and the core being the middle layer. Faces are two strong outer laminae and the core is a lighter material. The most common sandwich structure is a honeycomb [5].

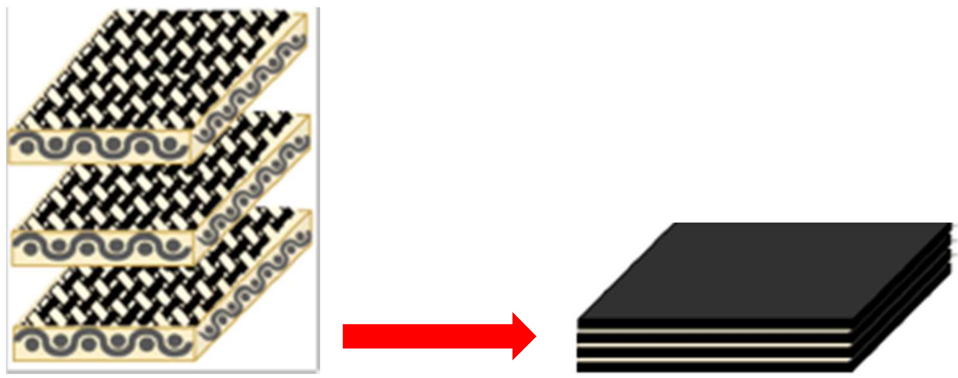


Figure 1.4: Laminar composite from [5]

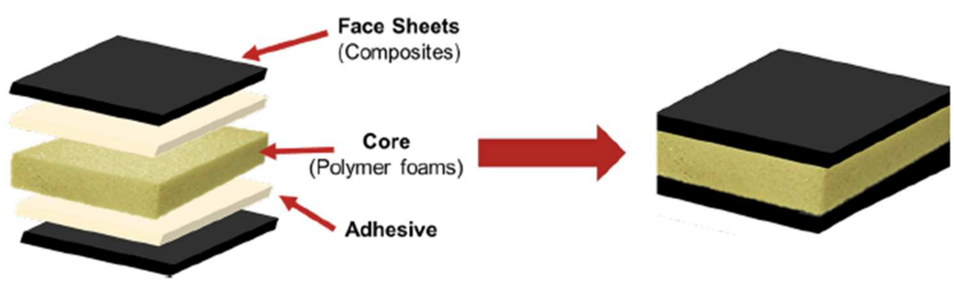


Figure 1.5: Sandwich composites from [5]

For research purposes, some scientists add more reinforcements to enhance the mechanical properties of the composite material.

MATRICES

There are different types of matrices such as ceramic, metal, and polymer. All three of these can transfer loads between fibers and a matrix.

Ceramic matrices are often used for space, gas turbine components, and nuclear applications due to its high-temperature resistance, lightweight, high thermal shock resistance, and non-conductive properties [6].

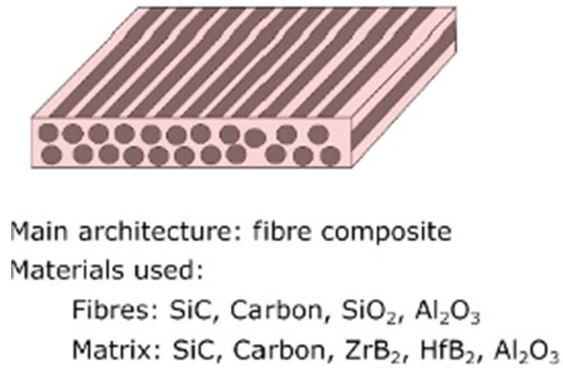


Figure 1.6: Ceramic matrix from [6]

A metal matrix is utilized in aircraft components, space systems, and sports equipment. This type of matrix has excellent electrical and thermal conductivity and is resistant to damage that can be caused by radiation.

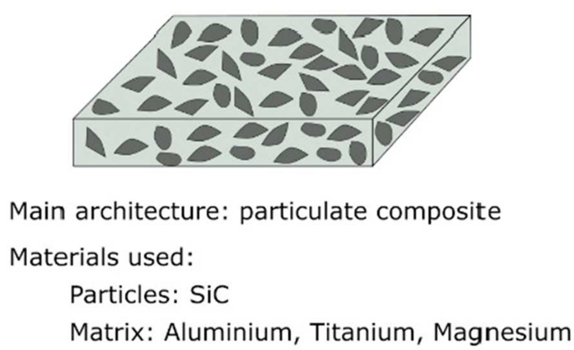


Figure 1.7: Metal matrix from [6]

Polymer matrices have high stiffness and strength properties and are lightweight. Polymer matrices can transfer loads between fibers and a matrix. While it is manufactured, the polymer matrix is called resin. A polymer resin is combined with a catalyst to speed up the process of solidification or curing, which may take hours to complete. After curing, the resin is called a matrix. There are two types of polymer matrices, thermoset, and thermoplastic. Thermoplastics are formed and shaped by heat and pressure processes. They do not undergo a chemical reaction, therefore, thermoplastics can be reheated and reversed into its original shape or another desirable shape. Thermoplastics have a much higher interlaminar fracture toughness than thermosets. Thermoset contains a curing agent to reinforce the material. Since thermosets undergo a curing process (chemical reaction), they cannot be reversed or reshaped [7,8].

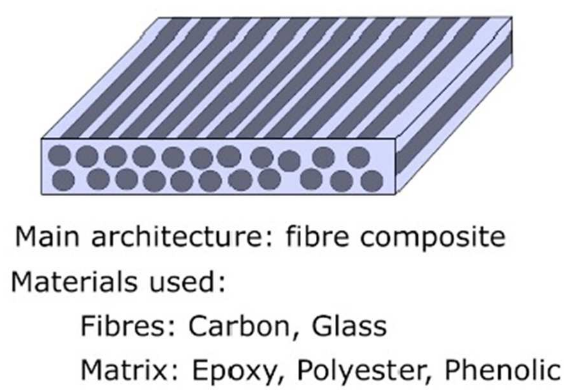


Figure 1.8: Polymer matrix from [6]

INTERLAMINAR REGION

Composite materials have excellent in-plane mechanical properties but not in the through-thickness direction. Figure 1.9 shows the different plane orientations. Orientation 1 is the in-plane direction, which is the direction of the fibers. Orientation 2 is the transverse direction, and orientation 3 is the out-of-plane through the thickness of the fiber.

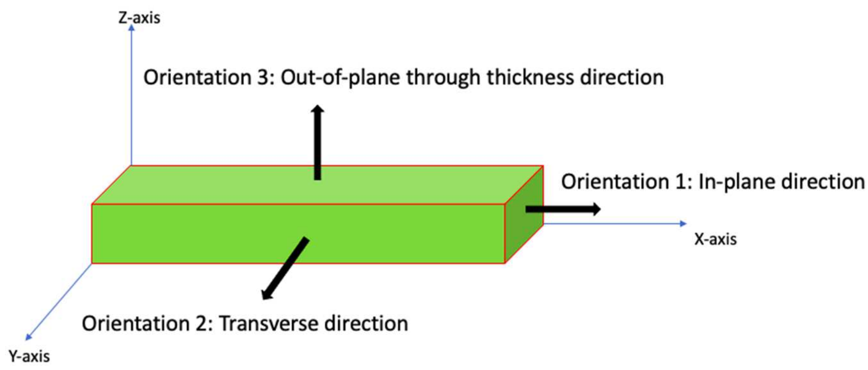


Figure 1.9: Plane orientations

A major drawback of composite materials is their interlaminar region, which is a resin-rich region located between the layers of fibers. This region is what makes the through-the-thickness properties extremely weak because there is no reinforcement in this area. Figure 1.10 is a visual representation of fiber and resin-rich in a composite.

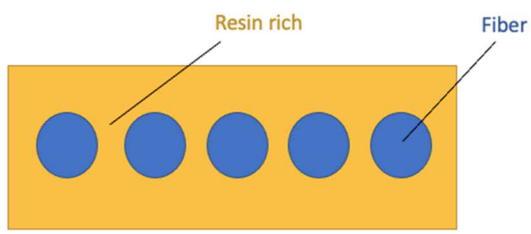


Figure 1.10: Interlaminar region

Due to the difference in mechanical properties between the constituents of composite materials, cracks can propagate in the intralaminar, interlaminar, or translaminar direction. As shown in figure 1.10. The intralaminar crack will propagate within the matrix. Interlaminar crack propagation is located between the layers of a composite. For example, between layer one and layer two. The translaminar crack will propagate within the fibers. The most common type is an interlaminar failure, which can lead to delamination, and ultimately to premature failure of the composite structure [7]. Delamination is the separation of layers of the composite caused by load or poor adhesion of the resin to the fiber layers. There have been several attempts to strengthen the interlaminar region. In the next section, it will be discussed the different interlaminar reinforcements, their advantages, and disadvantages.

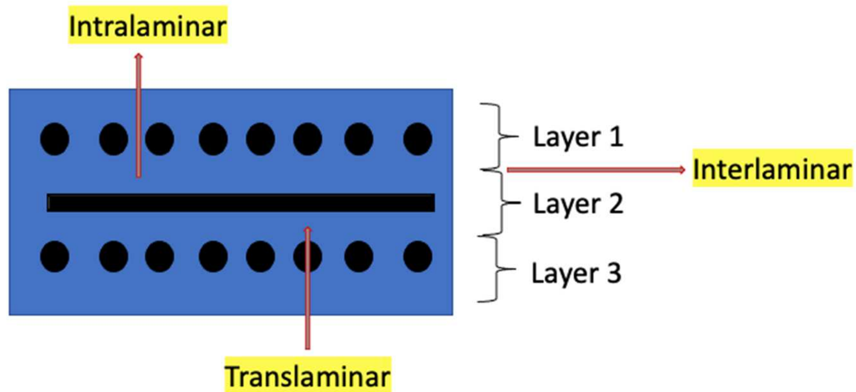


Figure 1.11: Intralaminar, translaminar, and interlaminar

INTERLAMINAR REINFORCEMENT

The materials used and the manufacturing process of the composite influence the interlaminar fracture toughness. Interlaminar fracture toughness is the flawed, cracked, or damaged material within the interlaminar region in a composite. Although materials degrade and fail due to time, wear, and/or manufacturing processing, there are many ways to improve the interlaminar fracture toughness. For instance, matrix modification, fiber surface modification, interlaminar reinforcement, interlayer materials, and micro-nano fillers.

MANUFACTURING PROCESSES

Stack-Up and Lay-Up Processes

Laminates may be manufactured by a stack-up and lay-up process. The laminate stacking and laid-up structure reduced the rate of energy, meaning that delamination is delayed. These methods are used to suppress interlaminar fracture. A lamina stacking consists of several layers of plies stacked together. The layers stick together by adding resin and a catalyst, which undergoes a curing process. By alternating the stacking sequence of the laminate, loading reversal occurs, which changes the interlaminar/intralaminar from tensile to compressive. Nonetheless, this advantage also disappears due to simultaneous stress reversal. There is another process similar to lamina stacking. Laid-up configurations can be out-of-phase/folded, iso-phase/stacked, and random configurations, hence, figure 1.12. The out-of-phase configuration has a mirror-like pattern and has unexpected results. The iso-phase configuration, which has a symmetrical pattern, has a significant effect because of the weaving offset. The random configuration did not show improvement in the interlaminar fracture toughness.

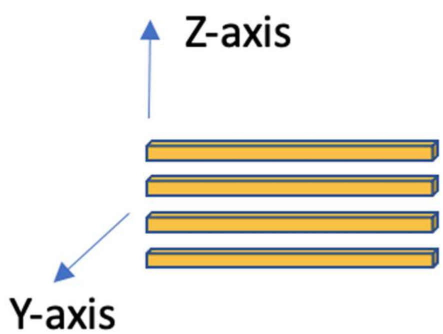
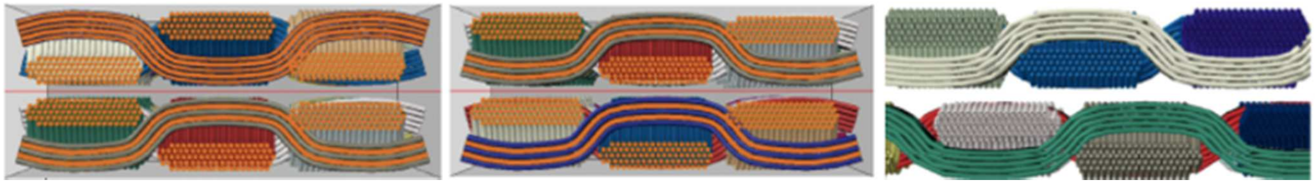


Figure 1.12: Lamina stacking



Out-of-phase *Iso-phase* *Random phase*

Figure 1.13: Laid-up configurations from [12]

Autoclave, Quickstep, Hot Press

The manufacturing process of composite material has an influence on the interlaminar fracture toughness. Manufacturing processes such as autoclave, Quickstep, and hot press are used to decrease the number of voids and air pockets. When a specimen is fabricated by autoclave and Quickstep, fracture toughness is increased. An autoclave machine is also known as the “wet heat”. It uses steam under pressure for sterilization. Quickstep fabrication will promote fiber bridging and higher fiber and matrix adhesion performance. This manufacturing process is an out-of-autoclave innovation used for defense and aerospace applications [13]. Furthermore, the average fracture toughness of the hot press fabrication was reported to be higher than the laminated prepared by autoclave and Quickstep [13,14,15]. In figure 1.14, the different types of manufacturing processes are displayed.

Autoclave (a) *Quickstep* (b) *Hot press* (c)

Figure 1.14: Manufacturing processes from (a) 13, (b) 14, and (c) 15

Matrix Modification

Matrix modification is enabled by toughening epoxy through the addition of modifiers. Epoxy has useful properties such as high adhesive strength, hardiness, and desirable resistance to chemicals and heat. However, epoxy is weak due to poor resistance to cracks, low fracture toughness, and low impact strength. Essentially, epoxy materials are brittle in nature. Modifiers are used to enhance the fracture toughness of the epoxy, which has been successfully tested, but at the same time, the mechanical properties of the matrix are degraded.

Some examples of matrix modifiers are thermoplastics and thermosets. As previously mentioned, thermosets cannot be reshaped or modified again once it is cured. Therefore, thermosetting composites can't be reused once their life expectancy is over causing environmental and cost issues. On the contrary, thermoplastic composites have many advantages such as high fracture toughness, and high impact resistance, and can be reused much longer. Although thermoplastic composites possess many ideal mechanical properties, the interlaminar properties are decreased in the in-plane direction. When the laminate is subjected to a load, the formation of cracks will appear causing delamination.

Fiber Surface Modification

In a fiber-reinforced thermoplastic composite, there are a couple of reasons the interlaminar mechanical properties are decreased. One reason is the weak interphase bonding performance between the resin and the fiber of thermoplastic prepregs. This issue is fixed with fiber surface modification. Fiber surface modification can be achieved by promoting strong fiber and matrix adhesion at the interface region, as shown in Figure 1.15. Fiber surface modification may be achieved by heat treatment, surface coating treatment, plasma treatment, high energy ray irradiation treatment, sizing agent treatment, and carbon nanotubes (CNTs) reinforcement. Oxidative is classified as a surface coating treatment. Oxidation treatment uses carbon fiber on the surface to produce oxygen-containing groups that possess high surface polarity, improving carbon fiber's surface wettability and promoting its bonding strength with the resin matrix. Plasma treatment ionizes gases into atoms, molecules, ions, electrons, and substances containing metastable and excited states. Such as oxygen, nitrogen, and ammonia. Radiation irradiation treatment adjusts the surface properties of the fibers by atoms or electron excitation displacement in the lattice. Sizing agent treatment changes the structure and the properties of the interface layer of the composite by applying a polymer sizing agent layer to promote adhesion between the fiber and the matrix. CNTs treatment can be performed by chemical grafting and chemical vapor disposition. These methods enhance surface wettability which promotes fiber and matrix adhesion. However, these methods also damage the fibers [17].

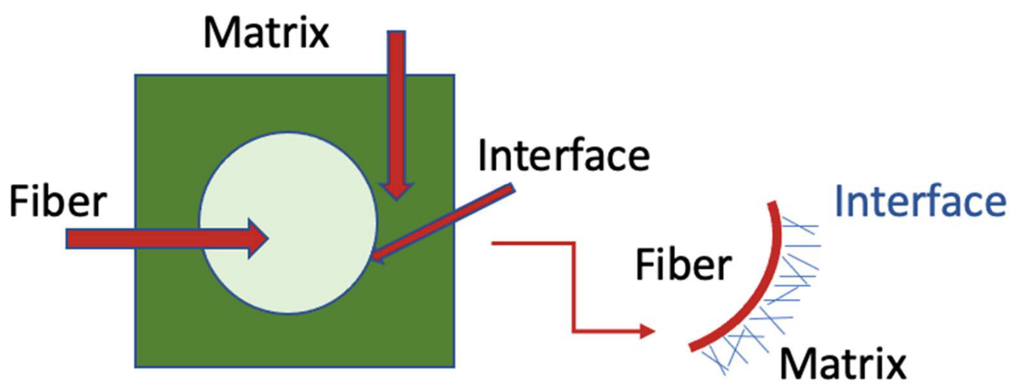


Figure 1.15: Interface region

The second reason interlaminar mechanical properties are decreased is the lack of reinforcement in the resin-rich area between the layers of the laminate. The resin-rich area can be improved by toughening the matrix. The integration of thickness reinforcement is ideal to reduce delamination and impact damage. As previously discussed, a composite material is weak in the through-thickness direction. A 3D sandwich structure reinforces this direction in 4 different manners. By braiding, stitching, Z-pinning, and 3D weaving. These methods greatly affect the interlaminar fracture toughness; however, the in-plane mechanical properties are diminished.

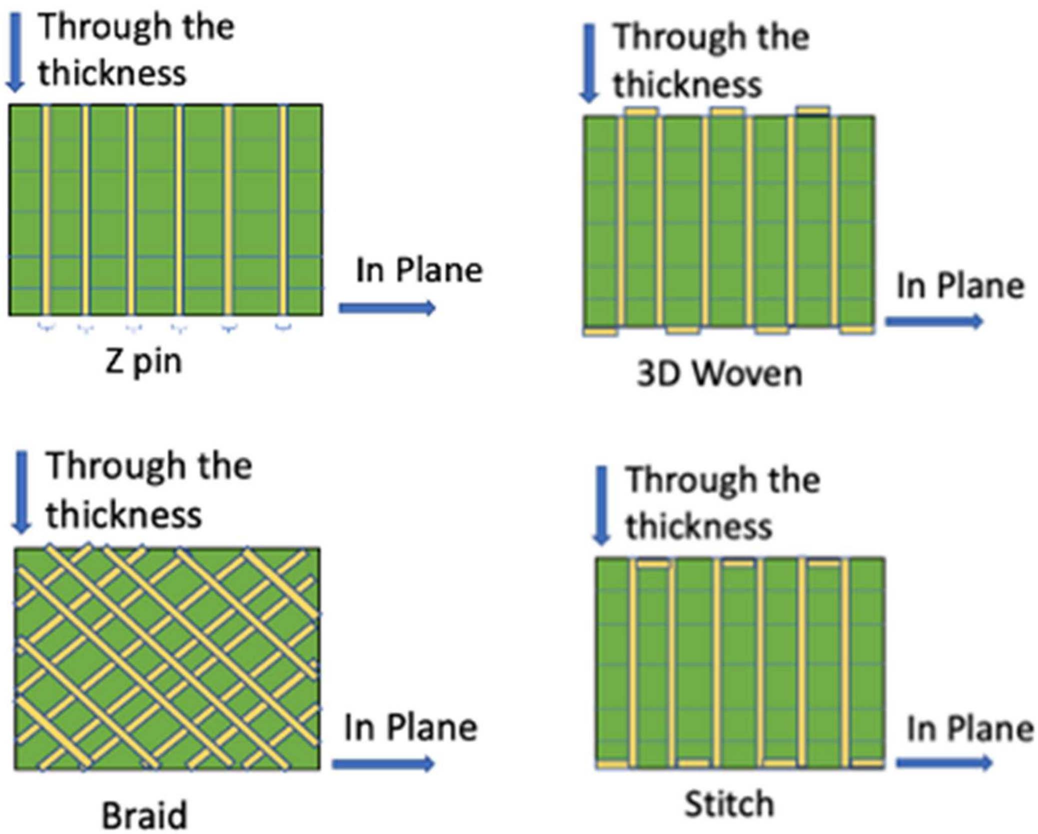


Figure 1.16: 3D Sandwich structures

Interleaf Layering

Interleaved composite is adding a thin film of material between the fiber interface to create another layer. This method will enhance interlaminar fracture toughness as well as decrease delamination. Adding an interleaved layer will decrease the fiber's modulus and tensile strength due to decreasing fiber volume fraction [18].

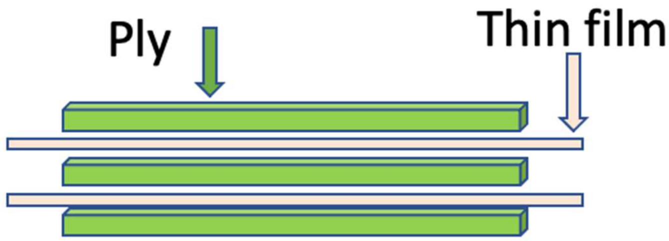


Figure 1.17: Interleaf layering

Multiscale Reinforced Composites

Polymer nanocomposites are used as advanced materials due to their improved resistance to delamination without damaging or jeopardizing the in-plane direction. Nano modification results in a multiscale composite. Multiscale reinforced composites are three-phase nano-composite that consists of a nano-size matrix, nano reinforcement, and reinforcement fibers. Carbon nanotubes (CNTs) are graphene layers in a tube at a nanometer scale. For fiber-reinforced composites, CNTs are the most commonly used nanofillers. Carbon nanofibers consist of nanostructures shaped like a cylinder, which are layers of graphene organized as cones. CNTs and CNFs are nanofillers based on carbon and are frequently used to increase the thermal and electrical conductivity of polymeric composites. The presence of nanofillers will promote the bridging effect, leading to propagation delay. The most often used methods for composite constituent modification are bulk matrix and fiber modification. In a bulk matrix, nanofillers are uniformly separated in the resin or matrix.

Fiber Modification

Fiber modification is an implementation in the growth of nano-reinforcements on the surface of the fibers or nano-reinforcements of the sizing of the fibers. Another method for interlaminar reinforcement is placing the nano-reinforcements between the layers of the laminate. In figure 1.17 the different methods for composite constituent modification are shown. The blue color represents the type of modification and how it would be displayed. [19,20]

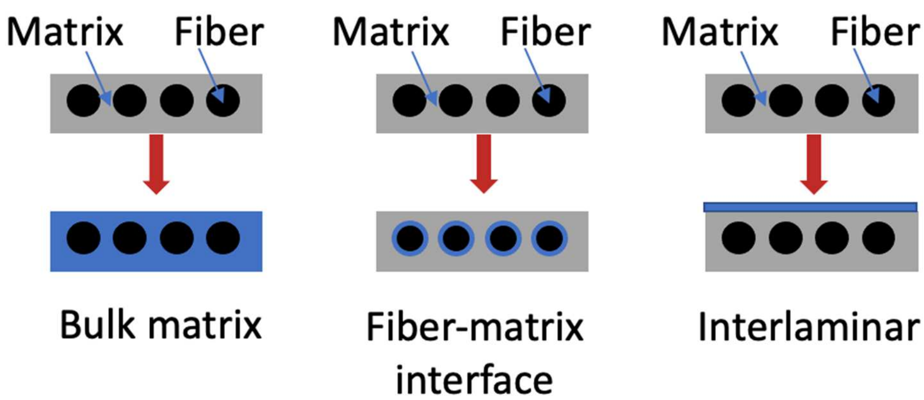


Figure 1.18: Types of composites modification

Second Reinforcement

A composite material must have a high damage tolerance to sustain any type of defect that is already in existence. Regardless if the material is defective, the design must ensure safety and functionality when used in industrial applications. As previously mentioned, a second reinforcement may be added for an interlaminar fracture toughness increase. In this research, carbon fiber will be used as a reinforcement, vinyl ester/epoxy as the matrix, and aramid pulp as a second reinforcement.

Aramid Pulp

Aramid pulp (AP) are micro/nano highly fibrillated chopped aramid fibers that are used for matrix modification or interleaved layers for interlaminar reinforcement. AP and aramid fibers possess desirable mechanical properties, chemical, and thermal stabilities. AP provides great fiber and matrix adhesion which will lead to toughening the interlaminar region by containing free fiber ends that will enhance the bridging effect. Aramid pulp is commonly used for carbon fiber-reinforced polymers (CFRP). It is a preferred reinforcing method because it will increase the strength of the resin without damaging the fiber, as the previously mentioned methods do [21].

The next chapter will explain the behavior and outcome of a composite material when it’s impacted. Also, the AP with different amounts of reinforcement will be analyzed for further research in composite materials.

Chapter 2: Impact on Composites

IMPACT TESTING

Carbon fiber reinforced plastic (CFRP) composites are often used due to desirable mechanical properties such as high bending-to-stiffness ratio, fatigue resistance, and lightweight [20]. Nonetheless, the through-thickness mechanical properties are decreased when subjected to a low-velocity impact event. Impact testing is categorized as low-velocity or high-velocity impact. The high-velocity impact is considered to be greater than 10 m/s. The fracture is visible in the impacted area. On the other hand, low-velocity impact (LVI) testing is classified as anything below 10 m/s. An example of a low-velocity impact is like dropping a tool during maintenance [2]. LVI is critical considering that there is hardly any visible damage on the surface of the composite. The internal damage can result in a reduction of stiffness, strength, durability, and stability, and damage can only be seen through micro-analysis. Common failure modes are delamination, fiber breakage, and cracking of the matrix. The most common failure mode is delamination. Z. Cheng, et al, demonstrated increased delamination toughness and improvement in the through-thickness direction when using Kevlar pulp as reinforcement in woven laminates subjected to LVI [22]. Even though the exact amount of Kevlar pulp has not been determined, Y. Hu, Y. Wei, G. Han, J. Zhang, G. Sun, X. Hu, F. Cheng have proven the increase and improvement of damage tolerance by using Kevlar pulp as reinforcement [22]. Studies have also shown that fiber-bridging properties are not present when interlaminar reinforcement is not used in a carbon fiber laminate. This leads to a decrease in cross-ply toughening and impact energy dissipation. However, excessive reinforcement may lead to fiber displacement as Kevlar pulp works its way into the gaps of carbon fiber laminate.

METHODOLOGY

Material Selection

Carbon fiber (3K weave woven) from FibreGlast was chosen because it mitigates crack propagation. Vinyl ester resin (#1110) from FibreGlast (Fibre Glast Developments Corp.,OH, USA) was used because of its UV, corrosive resistance, and low viscosity. For vinyl ester resin catalyzation, Methyl Ethyl Ketone Peroxide (MEKP) was used as a hardening agent. As an interlaminar reinforcement, Kevlar pulp (fibrillated aramid pulp) from FibreGlast was applied in between the carbon fiber layers. Kevlar pulp acquires agglomerated microfibers with a length between 0.5-1.7 mm and a diameter between 10-20 µm. The mechanical properties of each material are seen in table 1.

Table 1: Mechanical properties of each constituent material

	Woven Carbon Fiber[22]	Vinyl-Ester Resin[22]	Kevlar® Pulp[22]
Tensile Modulus (GPa)	227.5 - 240.6	3.7	58.8
Tensile Strength (GPa)	4.2 - 4.4	0.0827	--------------
Density (kg/m^3)	1750 - 2000	1.800	1400
Nominal Thickness (mm)	0.3048	--------------	--------------

Composite Fabrication

Each layer of weave woven carbon fiber was cut 150 mm by 100 mm (6x4 inches respectively) to create a 16-layer laminate, hence figure 2.1, according to the ASTM

D7136/D7136M-20 standard. These laminates were divided into three different groups according to their Kevlar pulp-to-resin ratio; 1X, 2X, and 4X.

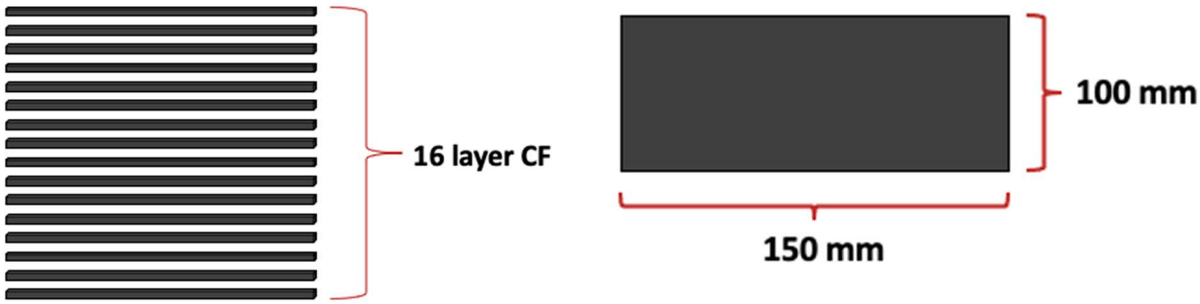


Figure 2.1: 16 layers of Carbon fiber & dimensions

The vinyl ester resin was catalyzed with Methyl Ethyl Ketone Peroxide (MEKP) hardener for reinforcement with a mass ratio of 100:1.25 following the manufacturer’s instructions. Before mixing, vinyl ester and MEKP were measured separately. When catalyzed, the resin and the hardener exposed a different color.

Table 2: Each reinforced laminate’s manufacture quantity

Reinforced (R) laminate name	Aramid chopped fiber	Vinyl ester resin	Methyl Ethyl Ketone Peroxide MEKP
 1X	 ½ full cup	 180 grams	 1.25%

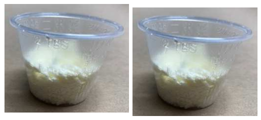
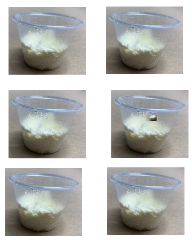
 2X	 1 full cup	 180 grams	 1.25%
 4X	 3 full cups	 275 grams	 1.25%

Table 2 illustrates each material's measurements used for 1X, 2X, and 4X carbon fiber laminates. For manufacturing 1X laminate, ½ of a one-ounce clear plastic cup of Aramid chopped fiber (Kevlar), 180 grams of vinyl ester resin, and 1.25 percent of Methyl Ethyl Ketone Peroxide (MEKP) for catalyzation were used. The 2X laminate manufacturing process used the same amount of vinyl ester resin and MEKP as the 1X laminate, with the difference of 1 full cup of Aramid chopped fiber. Lastly, the 4X laminate used 3 full cups of Aramid chopped fibers, 275 grams of vinyl ester resin, and 1.25 percent of MEKP.

Kevlar pulp initially comes in "closed/clumped" form, which is agglomerated fiber pellets. A coffee bean grinder was used to mechanically "open and separate "the "closed" pellets. The coffee bean grinder operated in three, 20 seconds bursts at 20,000 revolutions per minute (RPM) with a pause every time each burst.

Low-velocity impact (LVI) testing

A rectangular composite material with dimensions of 150 mm by 100 mm was analyzed for impact testing using a CEAST 9349 Drop Tower Impact System. A drop weight impact testing machine will determine the impact energy and velocity that is required to break or damage a composite material internally. The mentioned composite material is placed between two metal fixtures and a circular testing area. A demonstration of the specimen and the circular testing area is shown in figure 2.1. A striker is impacted on the center of the laminate in the through-thickness direction. The kinetic energy formula is used to obtain the striker's height and velocity.

$$KE = \frac{1}{2}mv^2 = mgh = PE$$

Where KE is kinetic energy in Joules (J), m is the total mass of the striker in kilograms (kg), v is the striker's velocity in meters per second, g is the gravitational acceleration in meters per second squared ($\frac{m}{s^2}$), h is the initial height of the striker in meters (m), and PE is potential energy in Joules (J). After impact testing, the data acquisition system (DAS 8000) will record energy, displacement, force, and time data. This data will be used for analyzation of Kevlar pulp reinforcement comparison between 1X, 2X, and 4X.

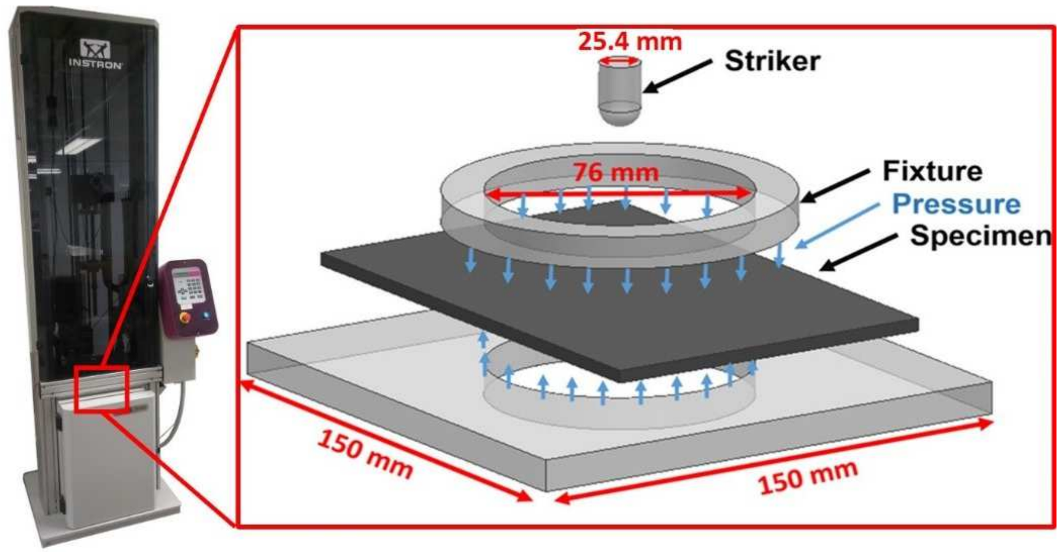


Figure 2.2: Testing area from [20]

RESULTS AND DISCUSSIONS

Carbon fiber composites that contained 1X, 2X, or 4X interlaminar reinforcement were analyzed after a low-velocity impact test. The data given by the acquisition system were time, energy, displacement, and force in which graphs such as energy-time, force-time, and force-displacement were obtained. The maximum displacement, absorbed energy, and bending stiffness are gathered by observing the force-displacement graph. In the energy-time graph, the degree of damage is calculated. The maximum force (peak force) and the duration of the impact are determined using the force-time graph.

Force vs Displacement

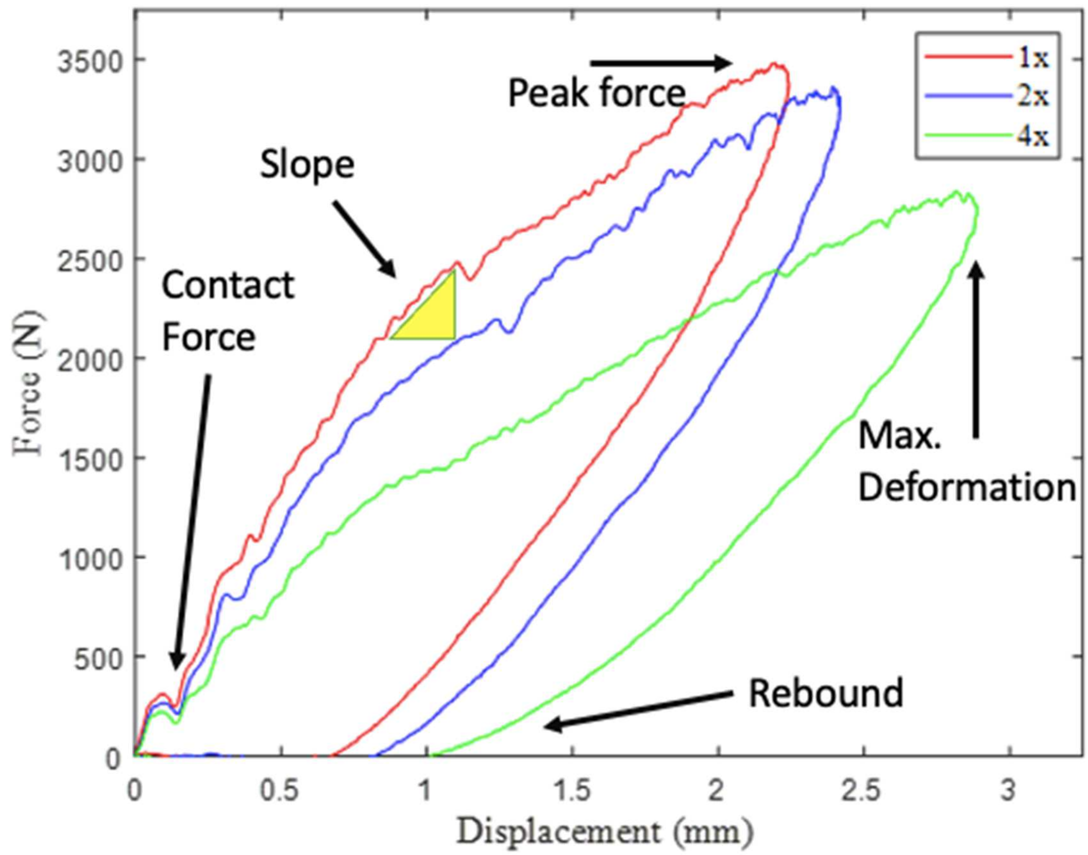


Figure 2.3 shows a representative force-displacement curve of samples impacted at 5J containing 1XR (red) 2XR (blue) and 4XR (green) Kevlar reinforcement.

Table 3: Maximum Displacement and Maximum Force for reinforced ratios 1X, 2X, 4X

Reinforcement Ratio	1x	2x	4x
Maximum Displacement (mm)	2.15 ±0.04	2.43 ±0.06	3.06 ±0.04
Maximum Force (N)	3450 ±40	3300±20	2740 ±20

As seen in Figure 2.2, the curve from all laminates demonstrates the correlation between the peak force and the displacement of the laminate while being impacted. The laminates that were impacted at 5J possessed different measurements of Kevlar reinforcement. By looking at the three graphs, it can be concluded that there was a rebound from the striker while the striker and the laminates were in contact. The curve lines from the laminates show that there was damage on the laminate before reaching the maximum force or peak force. After the peak force, the curve lines decline inwards, meaning that there was a rebound. The area in the enclosed section of the graph will demonstrate how much the laminate was damaged. By analyzing the force and displacement graph, 1X reinforcement shows that the area under the curve is smaller than 2X and 4X reinforcement laminates and that the maximum peak force is higher in the 1X reinforcement. Overall, the laminate containing 1X reinforcement displayed more desirable mechanical properties than 2X and 4X reinforcement.

Energy vs Time

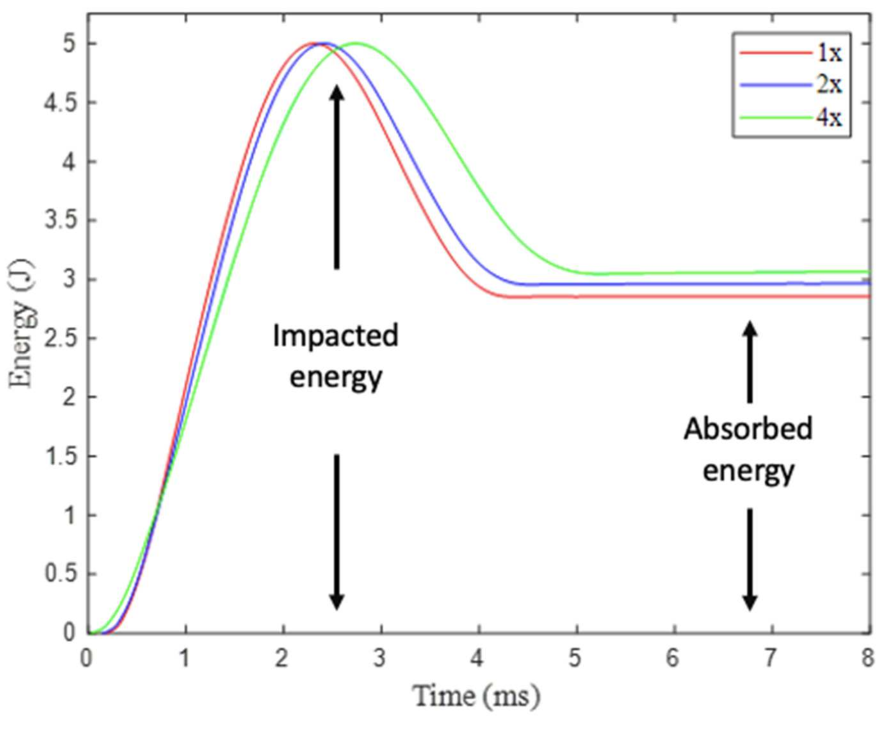


Figure 2.4 shows a representative energy-time curve of samples impacted at 5J containing 1X (red), 2X (blue), and 4X (green) Kevlar reinforcement.

Table 4: Degree of damage of laminates after impact testing

Laminate	Energy Absorbed	Impacted Energy	Degree of Damage	Type of Damage	St. Dev.	Average
1X	2.4	5J	0.48 or 48 %	Penetration	0.05	0.48
2X	3.01	5J	0.61 or 61 %	Penetration	0.03	0.61
4X	3.87	5J	0.78 or 78 %	Penetration	0.06	0.78

The values for the degree of damage of all laminates with 1X, 2X, and 4X reinforcement are shown in table 5. It can be concluded that the more Kevlar reinforcement is added to a laminate, the degree of damage is greater than the laminate with 4X reinforcement by about 15%.

The absorbed energy is defined as the energy taken in by the laminate, the plateau section in the graph. This action denotes that the laminate is deformed by delamination, a crack in the matrix, or fiber breakage. The maximum energy on the graph is the peak value, which is known as the impacted energy. In Figure 2.4, the absorbed energy can be seen after the peak value, which is the steady line on the right side of the energy-time graph. The degree of damage can be calculated by obtaining the ratio of absorbed energy and impacted energy. Depending on the value that is gathered after calculating the degree of damage, we can determine if the laminate was perforated or penetrated. If perforation can be perceived, the laminate absorbed 100% of the impacted energy, meaning there was no rebound. However, there is a possibility that the laminate had penetration and a rebound if the laminate absorbed less than 100% of the impacted energy. The values for the degree of damage of all laminates with 1X, 2X, and 4X reinforcement are shown in table 5.

$$\text{Degree of Damage} = \frac{\text{Absorbed Energy}}{\text{Impact Energy}} * 100\%$$

Force vs Time

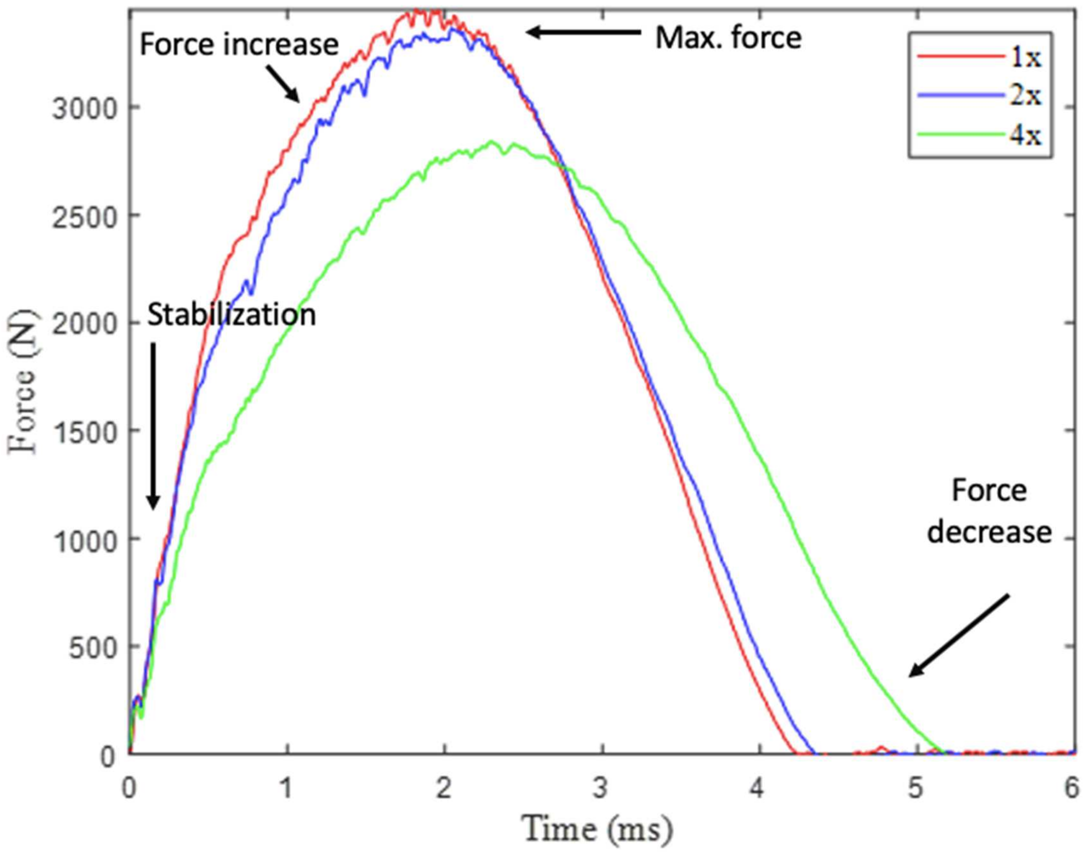


Figure 2.5 shows a representative force-time curve of samples impacted at 5J containing 1XR (red) 2XR (blue) and 4XR (green) Kevlar reinforcement.

Table 5: CFRP composites force-time for 1X, 2X, and 4X.

Reinforcement Ratio	1x	2x	4x
Peak Force (N)	3470 ±20	3360±30	2705 ±130
Impact Duration (ms)	4.2±0.75	4.4 ±0.6	5.3 ±0.69

Figure 2.5 shows four sections: stabilization, force increase, maximum force, and force decrease. A stabilization area is where no damage has occurred on the laminate. Force increase is

when multiple impacts occur before the maximum peak force. The maximum force is the total number of impacts at the maximum peak force, leading to a forced decrease due to damaged laminate. Force decrease is when the peak force and the stiffness are slowly reduced. By analyzing table 4, it is shown that the 4X interlaminar reinforcement has the least high peak force and the most increased impact duration than the 1X and the 2X. After examination, it can be concluded that the more resin-to-interlaminar reinforcement ratio also increases the total contact time with the striker. During the post-peak stage, the striker detaches from the laminate, which leads to a force decrease until it reaches zero. Figure 2.5 shows that 4X reinforcement has a larger duration time than 1X and 2X reinforcement due to the formation of damage in the laminate leading to decreased stiffness. The connection between a laminate with an increase in reinforcement results in a lower peak force and higher impact duration. The impact duration connects to the presence of air during manufacturing. Air is present in the fibers leading to a decrease in stiffness.

Contact force is defined as the moment the striker and the laminate initially make contact, figure 2.5. The contact force between the striker and the laminate was used to obtain the force-time graph. Figure 2.5 shows the force-time curve of samples impacted at 5J with 1X, 2X, and 4X reinforcement. The laminate with 1X reinforcement recorded a maximum force of 3428 and an impact duration of 5 ms. The laminate with 2X reinforcement had a maximum force of 3159N at 4.8 ms. The laminate containing 4X reinforcement has a peak force of 2696 N at about 4.9 ms. It can be concluded that the laminate with 2X reinforcement has a higher peak force and that the laminate with the 4X reinforcement experienced more damage. Nonetheless, the laminate with the 1X reinforcement expressed a higher peak force than 2X and 4X reinforcement.

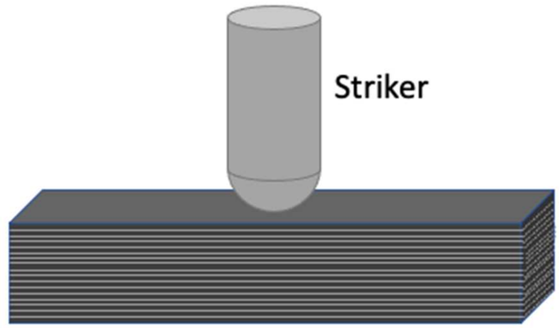


Figure 2.6: Contact force

FRACTOGRAPHY ANALYSIS

A fractography was used to analyze and determine the damage in the 16-layer carbon fiber laminate with 1X, 2X, and 4X Kevlar pulp reinforcement. Figures 2.7 and 2.8 show the cross-section of the laminates from the left to right on the XZ and YZ view, respectively. It has been observed during the resin mixture manufacture process, the amount of Kevlar reinforcement increased, and a higher amount of air pockets or voids were present which are demonstrated in yellow in Figures 2.7 (a), (b), and (c). This increase of air within the matrix leads to an overall decrease in stiffness.

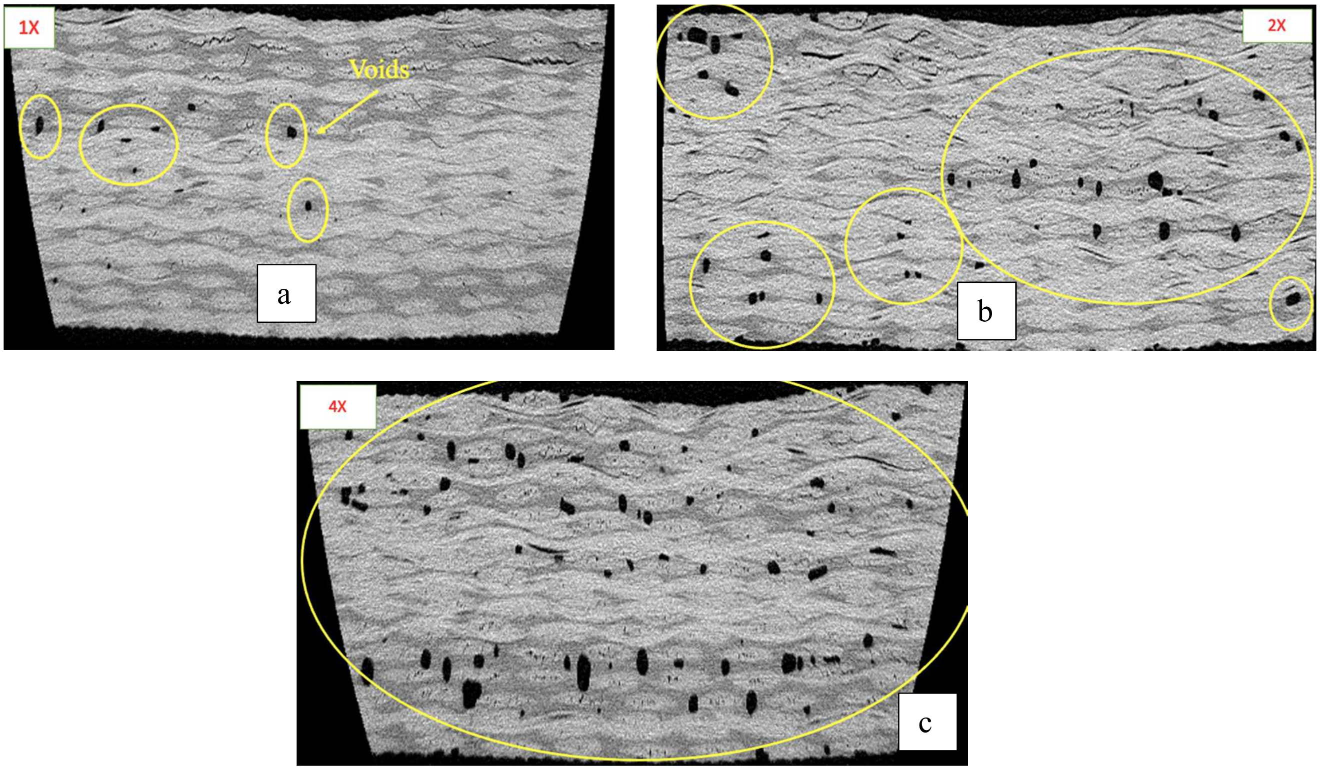


Figure 2.7 is a Fractography analysis image of (a) 1XR, (b) 2XR, and (c) 4XR in the XZ direction.

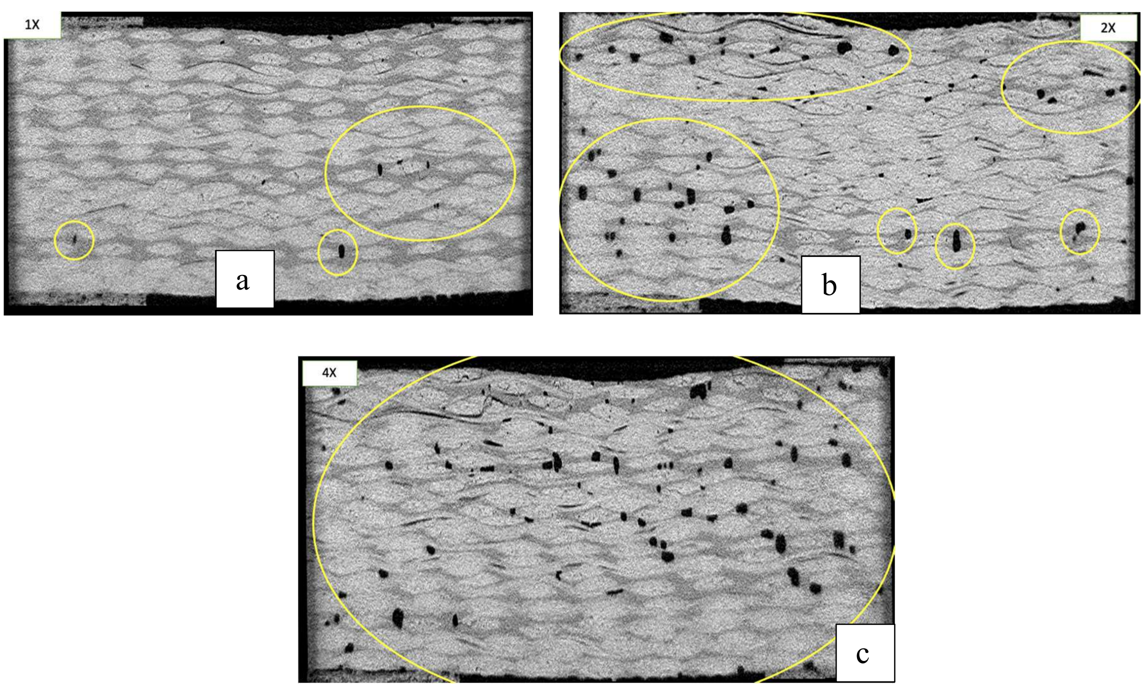


Figure 2.8 is a Fractography analysis image of (a) 1XR, (b) 2XR, and (c) 4XR in the YZ direction

CONCLUSION

In this research, carbon fiber reinforced polymer (CFRP) composite plates were reinforced in the interlaminar region using the layup method and different pulp-to-resin ratio mixtures of 1X containing 1:15 by volume, 2X with a ratio of 2:15, and 4X with 4:15 ratio mixture. Data such as energy, displacement, contact force, and time were recorded for comparison after CFRP composite plates were impacted at 5 J impact energy following the ASTM D7136-M20. This given data was analyzed and compared to make the subsequent observations:

- Force-displacement results showed an increase in deformation, meaning there was higher maximum displacement, an increase in absorbed energy, and a decrease in bending stiffness as Kevlar pulp ratio mixtures increased.
- Energy-time results displayed an increase in the degree of damage on the CFRP plate as reinforcement increased.
- Force-time results observed a lower peak force with an increase of impact duration, allowing more space for damage as the interlaminar reinforcement ratio mixture increased.

It can be concluded that the stiffness decreased as the Kevlar pulp ratio mixtures increased. An observation made during the manufacturing process of the resin mixture is that increased amounts of air trapped in the microfibers were present, which lead to a stiffness decrease.

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Curriculum Vitae

Daisy H. Mariscal was born in El Paso, Texas, United States on January 5, 1992. She started college at El Paso Community College and earn an associate degree in Liberal Arts. Later in 2018, she transferred to the University of Texas at El Paso with the pursuit of a bachelor's degree in mechanical engineering. She worked at the University of Texas at El Paso for a Summer Institute called ExcITES in 2019. That same year, she started working as a hybrid tutor at ACES, assisting other students with engineering, mathematics, and science classes. In Spring 2021, she earned a bachelor's degree in mechanical engineering.

In Fall 2021, Daisy started graduate school for a master's in mechanical engineering. She earned a Master of Science in mechanical engineering degree in Fall 2022.

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