Instituto Tecnologico y de Estudios Superiores de Monterrey
Campus Monterrey

School of Engineering and Sciences

Evaluation of Forged composite on 3D Carbon Fiber composites for exoskeletons

A thesis presented by

Miguel Alejandro Pérez Salazar

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Abstract

Composite materials have been widely used in recent years for their outstanding mechanical properties in different industries, especially aerospace and automotive. However, the use of these materials has impacted the development of Exoskeletons to increase physical performance to complete specific tasks or movements in the human body. Exoskeletons have been developed using aluminum and different alloys, but it has been migrated to the composite material. The evolution of the composite material to 3D woven has shown good out-of-plane mechanical properties. In most cases, composites are developed by infusion processes even though compaction has proven an increase the mechanical properties. The research aims to create an infusion and compression manufacturing system to produce 3D composite materials, delivering stable and better mechanical properties for exoskeletons components. Several experiments and tests were developed to define the best manufacturing process based on the resin distribution and the mechanical properties obtained. The mechanical properties of 3D woven composites were improved using infusion and compression molding by ensuring better impregnation and distribution of the resin through the composite and increase the mechanical properties significantly for tension and flexion. Finally, it was applied in designing a component of an exoskeleton, obtaining a saving in weight and reduction of volume.

Dedicatory

To my family, my parents M. Pérez Hernández, F. Salazar Bazaldua,

My sister J. Pérez Salazar,

and my partner R. A. Gámez Espinosa.

For their love, patience, understanding and support.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Problem Statement

In recent years, the demand for transportation and movement around the world has been increasing significantly. According to oxford economics air passenger grew to 8.8, 4 and 11.6 percent on Europe, United States and Asia respectively in June of 2017. The forecast on the air passenger trip frequency is expected to continue growing in the next 20 years, in which emerging economics like Brazil and Mexico expect growths of 5 and 4 percent respectively [1, 2].

Global market growth started demanding more and better airplanes, leading the aerospace manufacturers to create and produce new airplanes with better characteristics; that can only be sustain by the development of new materials. Not only the sports, aerospace, and automotive industries, but also the designers & developers of exoskeletons have begun a new journey searching for new and better materials and manufacturing process that can not only guarantee the demanding requirements, but can also give them a competitive advantage on the market [3, 4]. Driven by the need to produce these new materials and the steady growth on the transportation market the demand for composite materials and production has been increasing widely around the world as shown in Figure 1.1, which shows the growing tendency that the composite materials have been dragging recent years and how it is expected to keep growing.

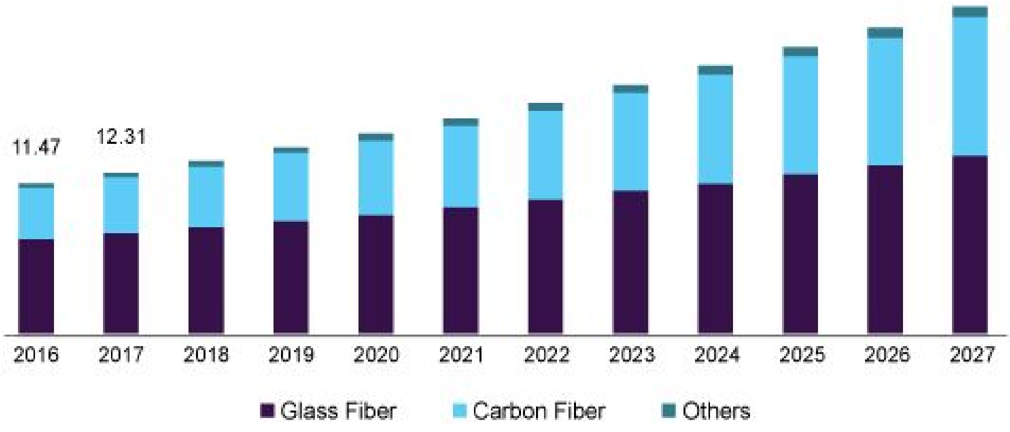


Figure 1.1: U.S. composites Market size, by product, 2016-2027 (USD Billion) [5].

1.2 Study Justification

The aerospace market has risen considerably in recent years, in 2018 enterprises such as General Electric (GE) Aviation and CFM international announced more than twenty-two billion in orders and commitments for jet engines, avionics, services and others; and, it is expected to keep growing, as mentioned by Wagner, it is expected to become a six trillion worth industry from 2017 to 2036; companies like Boeing anticipate sales of forty-one thousand new airplanes through to 2036. This growth has also demonstrated substantial impacts in different areas such as Oklahoma in which has been demonstrated that forty-four billion dollars in annual economy activity are produced by the aerospace market [6, 7]. Countries like Puerto Rico have benefited projects like the state-of-the-art aviation maintenance, repair and overhaul are a clear benefit of the positive impact that the industry could make on society. With the creation of jobs, incomes, and others [8]. In Mexico there is not an exception, the aerospace industry picture as one of the most important markets in the near future. According to the Economista, the aerospace industry has reached a growth rate of 11.2 percent per year, and in 2015 Mexico was placed at world level in receiving foreign direct investment projects [9, 10]. Figure 1.2 shows the impact of the aerospace industry in Mexico.

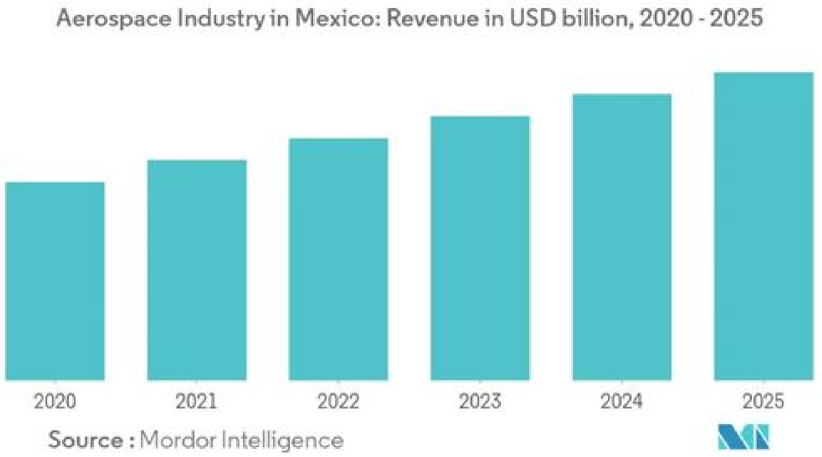


Figure 1.2: Aerospace industry in Mexico [11].

Aerospace growth represents a great focus of opportunity to new materials, manufacturing and equipment that could help to reduce costs, save weight, and improve the properties of the materials as needed. According to Wagner, only GE Aviation invests around eight to fifteen million dollars on new equipment to support the growth, safety and manufacturing technology to improve product quality and time cycle [12]. Open possibilities for searching constant innovation that could help their products to reduce costs, save in weight, and other benefits; that could give an important market advantage [13, 14]. One clear example of how does composite materials have helped the industry to save weight on the production of new airplanes is the LEAP engine that helps to increased fuel efficiency by 15 percent, and reduced NOx emissions & noise level by 50 and 75 percent respectively, that is why it is important to develop new and better materials that could help not only to increase efficiency, but also helps to promote the reduction of contamination [15].

Figure 1.3: LEAP engine [16].

1.3 Research objectives

This work aims to demonstrate and develop a compression manufacturing system to produce 3D composite materials, delivering stable and better mechanical properties.

Specific Objectives:

- To generate 3D woven materials.
- To improve the mechanical properties of the composite using the proposed manufacturing system (Vacuum assisted resin transfer molding/Compression molding).
- To validate the implementation of the system by using different resins as the matrix of the composite.
- To characterize the phase distribution of the composite.
- To evaluate the manufacturing processes with which the best mechanical properties are obtained on 2D glass fiber composites.
- To evaluate the manufacturing processes with which the best mechanical properties are obtained on 3D carbon fiber composites.

- To analyze the effects of compaction pressure, viscosity of the resin & temperature on the mechanical properties of the different manufacturing process on 3D carbon fiber composites.

1.4 Research Hypothesis

Mechanical properties of exoskeleton components can be improved using 3D woven composites developed by compression molding by ensuring better resin distribution and impregnation through the composite by strengthening the interlockingbounding between matrix and fiber.

1.5 Variables

On this work the following variables will be explored to understand the effects of each variable (temperature, matrix viscosity and compaction) on the mechanical properties and manufacturing processing of the 3D woven composites. Only one fabric pattern (3D orthogonal weave) will be used as is the most hand made reliable fabric to develop.

- Fabric pattern.
- Temperature.
- Matrix viscosity.
- Compaction.

1.6 Independent variables

- Mechanical properties (Fracture resistance, improved elasticity, fatigue resistance).

1.7 Dependent variables

- Fabrics patterns.

1.8 Assumptions

The following assumptions would be considered in this research work:

1. Fabric construction parameters such as tow density, tow thickness and tow spacing are the same from weave to weave.
2. Woven fabric composites of various weaves contain an equal number of manufacturing defects like voids, porosity, and others.

1.9 Delimitation study

This work will focus in understanding how does the mechanical properties change according to the manufacturing process and the factors that affect the surface finish and composite development during his manufacturing. A study of the different manufacturing processes of 2D woven composites was also developed as a reference.

1.10 Definition of key terms

- Woven fabric - ancient technology interlace different linear materials in different patterns to form an integrated structure [17].

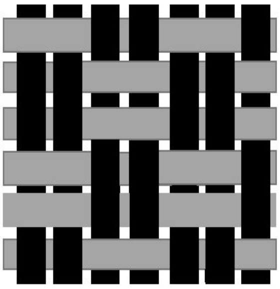


Figure 1.4: Woven fabric.

- Composite materials - the combination of two or more substances achieving different properties than the original materials that composed it. Characteristics have helped to developed new materials with superior properties over the conventional ones [18].
- Yarn - An assembly of mono-filaments held together [19].

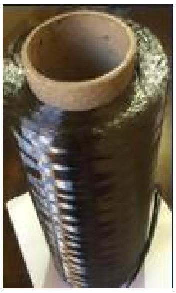


Figure 1.5: Yarn.

- Roving - A fiber band that consists of parallel oriented single filaments [20].
- Crimp - When a fiber yarn is curved in or out of the plane of the textile [21].

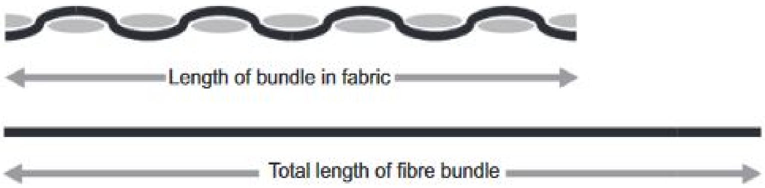


Figure 1.6: Crimp effect [21].

Chapter 2

State of the art

2.1 Historical framework

In recent years, composites materials have been widely use in different industries for their advantages compared to traditional materials as strength. Their use in critical areas and products have grown rapidly, leading to new and complex composite materials and structures [22]. Understanding their behavior from different perspectives is crucial to delimit the use and capabilities of these materials. Most used composites in recent years are fiber reinforced plastics (FRPs), in which carbon and glass fiber stand out. FRPs have been used in different areas like automotive, aerospace, security, building and sports industries. Some advantages of FRPs is their flexible development that can be adapted to many specific uses. Several changes on this materials can be developed which can improve the product performance in specific manners, changes like proportions of resins and fiber, as well as orientation, manufacturing processes, the addition of fillers and others [18, 23]. More advantages of FRPs are presented in Table 2.1.

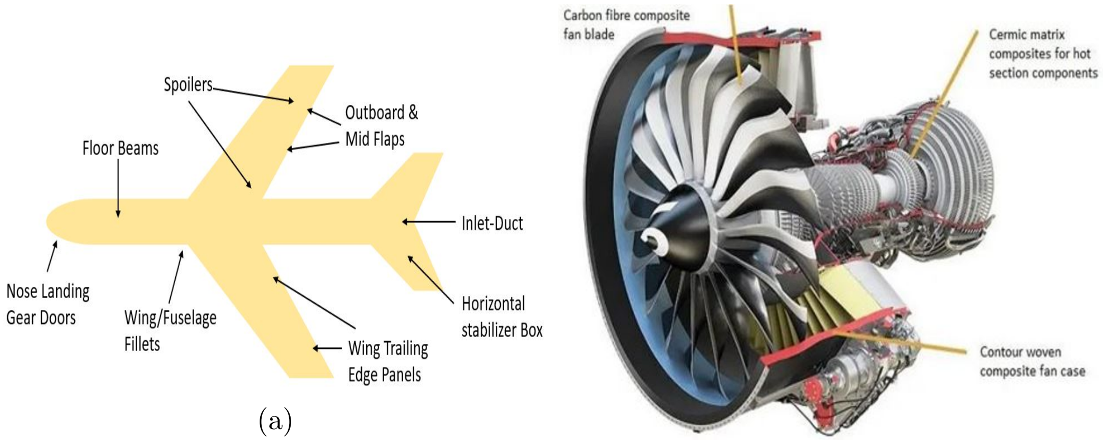
Table 2.1: Advantages of FRP

Advantages
Strength
Light weight
Non-conductive
Noncorrosive
Easy to mold
Flexible (Sustain more force and strain)

As stated before composites market have been growing widely as shown in Figure 1.1 and is projected to keep growing by 25.4 billion dollars as mentioned by [24]. Dividing this market on different segments we can highlight carbon fiber composites which has a potential growth of 11.4 percent and an expected growth of US$21.2 Billion by 2025 [24].

The presence of composites in the aerospace industry have a significant grown in recent years, as mentioned by [25]. Composites began to appear in structural applications for aircrafts at the early nineteenths in which the industry continued to mature and the material and processes became better to understand and more cost effective. By the pass of the time composite materials began to appear on commercial aircrafts. Research and development of high performance composite materials began to take a major role in different industries, universities, governments and institutions as the Air Force Research Laboratory. Many programs, as the Advanced Composites Technology Program (ACT), were developed searching to learned and understand the material capabilities and limitations on how can they be used in the industry [25].

Composites materials have also taken a leading role on passenger planes such as the McDonnell-Douglass aircraft MD-12X, and the airbus A340 which incorporates around 4000kg of carbon fiber RP structures [19]. Table 2.2 and Figure 2.1, are shown different examples of composite materials that have been used in the aerospace industry.



(a)

(b)

Figure 2.1: Composites aerospace applications: (a) Carbon fiber composites in the MD-12X airplane [19], (b) Carbon fiber LEAP engine [26].

Table 2.2: Composite materials on the aerospace industry

Part name	Material	Ref.
Boeing 787 composite window frames	Carbon fiber	[27]
Composite blades (AgustaWestland EH101 helicopter)	Carbon fiber	[28]
LEAP engine	Carbon fiber	[29]
Airbus A350 XWB and Boeing 787 dreamliner fuselage	Carbon fiber	[30]
Airbus A380 Fuselage	Glare	[31]

Composites materials are not only used in the aerospace industry, their impact has extended to other industries as the automotive. A clear example is the Lamborghini sports cars developed with forged composite as the L. *Murcielago* which presented almost an entire carbon/epoxy body. Despite the different disadvantages that this technology presented at the moment, as the low production rate, composites materials keep growing on the industry resulting on the evolution of new and more profitable cars as the *Aventadors*, that double the production volume, and the *Sesto Elemento* which was 80 percent carbon fiber reinforce plastics (CFRP), including its monocoque, front subframe, transmission shaft, exhaust, suspension components and crash boxes. *Sesto Elemento* project is shown in Figure 2.2. Benefiting not only the products' appearance and performance, but also the production process, transportation sector, fuel efficiency and the $C0_2$ emissions [32, 33, 34].

(a)

(b)

Figure 2.2: Lamborghini *Sesto Elemento* [35].

Nowadays carbon fiber composites have become more common and we can find these products on daily life as in non-sports automobiles, civil structures, tennis rackets, helmets 2.3, mass transportation, medical and other consumer products [19].

Figure 2.3: Snow sports helmet [36].

As an example, the sports industry carbon fiber composites have appeared as a breaking point in the development of new products like rackets, boats, bicycles, helmets and others. BMC had spent more than 51.8 million USD in developing materials, robotic processes and factories to produce of carbon bikes. Different engineer concepts like flexibility, material, fiber orientation, strength, stress, strain and others, took a leader role in the developing products [37]. Examples applications of different industries are shown in Table 2.3.

To accomplish the required properties on a specific application, the fibers arrangement within a composite should be decided to make them (fibers) able to bear the loads in the most effective way. Fiber architectures can be divided into 4 categories: discrete, linear (continuous), laminar (2D weave), and integrated (3D weave) [19]. Table 2.4 shows characteristics of each category.

Table 2.3: Composite materials applications

Part name	Material	Ref.
Snow sports helmet: Top shell, c-shaped strap and lateral shells	Glass fiber	[36]
Wind turbine blade	Glass fiber	[38]
Lamborghini Sesto Elemento suspension arms	Carbon Fiber	[32]
Windshield Surround Outer and Inner Panel, fender supports, Door Inner panels, sill to fender brackets and headlamp supports (Dodge Viper)	Carbon and glass fiber	[39]
Ship Bulkhead (Nautical applications)	Glass and Basalt fiber	[40]
BMW i3 electric car (CFRP body and recycled CFRP roof)	Carbon fiber	[41]
Boat building	Carbon fiber	[42]

Table 2.4: Fiber architecture characteristics [19]

Type of reinforcement	Textile Construction	Fiber Length	Fiber Orientation	Fiber Weave
Discrete	Chopped fibers	Short	Random	None
Linear	Filament yarn	Continuous	Linear	None
Laminar	Simple fabric	Continuous	Planar	2D
Integrated	Advanced fabric	Continuous	3D	3D

2.2 Exoskeletons

The constant pursuit of improvement, including itself, has driven humans to developed new materials and technologies to keep evolving and improve their physical performance and health. One of the most representative ways technology and new materials, as composites, can adapt to improve human health and condition are the exoskeletons. Exoskeletons are devices that work in harmony and parallel with their users in order to augment the physical performance of the individual, making him able to complete certain tasks or movements [43]. Exoskeletons can also be described as electromechanical devices that are used by a human operator and designed to increase the physical performance [44].

According to Grand view research the exoskeleton market is anticipated to reach 4.2 billion USD by 2027 expanding at a CAGR of 26.3%. This is due the growing adoption of exoskeletons in healthcare and non-healthcare settings, reimbursement coverage and increasing prevalence of spinal cord injuries (SCIs) [45]. However opposing opinions could be found on current exoskeletons from people who do not consider them a satisfactory alternative to the independence afforded by other devices as the wheelchairs [44].

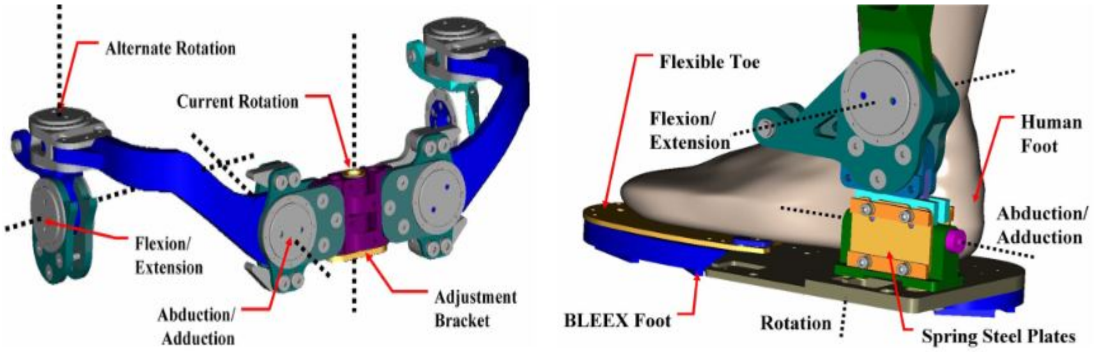
Exoskeletons can be used in any physical activity that a person can perform. However, weight, size, speed, efficiency, current technology & materials limits exoskeletons performance keeping them fully being exploited, despite the exoskeletons historical growing. That is why the creation of new and lighter materials is required in order to improve exoskeletons while increasing its application areas [43, 44].

Exoskeletons can be classified in different manners, for example, according to their structure (soft or rigid). A rigid exoskeleton is defined as an exoskeleton with a structure made of rigid materials, such as metal or plastic, while a soft exoskeleton is described as a structure made of textiles, they are also known as exo-suit [43].

Other characterizations of exoskeletons are:

- Type of action (active or passive).
- Technology powering.
- Purpose (assist & rehabilitate).
- Body part.
- Application area.

The development of computers and new dedicated softwares boosted modern exoskeletons, as for example the exoskeletons design which is improved wit the use of modeling and simulating software. An example of this could be presented on BLEEX (Berkeley lower extremity exoskeleton) [46], which is an assist exoskeleton which helps the user to carry an external load in addition to the exoskeletons weight. On Figure 2.4 there are examples of the CAD and modeling tools that were used on this work.



(a) (b)

Figure 2.4: BLEEX (a) Hip, and (b) Ankle degrees of freedom [46].

Body part exoskeletons are mainly focused on the lower body with a 56% frequency. This is due cause most of exoskeletons are designed to aid a used with mobility issues which are associated mostly with the lower part of the body. On the other hand specific joints have a frequency of 16% and upper body only 15%. Purpose as one of the most interesting categories on exoskeletons can be classified on Performance and recovery, there might be cases were both purposes are search during design. Over 59% of exoskeletons are used for performance, while 31% are sued for recovery, and only the 10% of exoskeletons have both (performance and recovery). This is due that recovery exoskeletons are focused on specific pathologies and patients, making them harder to mass produce than performance exoskeletons that have a more commercial use [43]. Figure 2.5 shows diagrams of the purpose and application area of the exoskeletons.

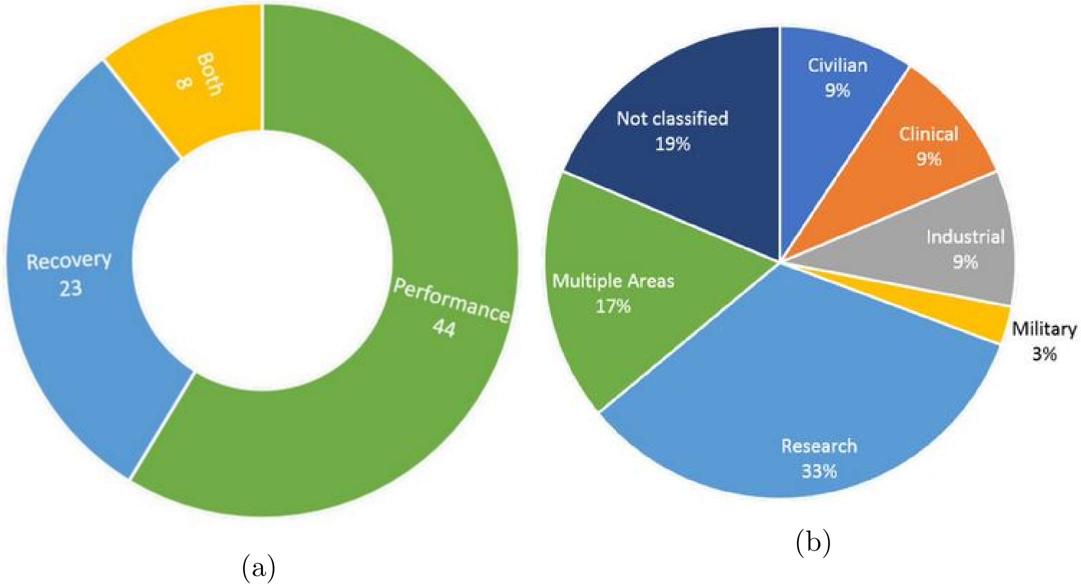


Figure 2.5: Exoskeletons (a) purpose, and (b) application area [47].

2.3 Composites

Composites consist of a reinforcing material joined by a binder (matrix). Fiber reinforced composites as their name implied consist of fiber embedded in or bonded to a matrix with distinct interfaces between them. In these composites the fibers are the primary source of strength and principal load-carrying members while the matrix acts as a load transfer medium, keeps them in the desired location and orientation, improves impact and fracture resistance, avoid crack propagation & growth and gives environmental resistance. Important desired properties of the matrix are shown on Table 2.5. The most common form in which FRC is used in structural applications is called laminate, which are made of stacking a number of layers of fibers and matrix consolidating them into the desired thickness. Fiber orientation in each later and stacking sequence can be controlled which helps to generate and control a wide range of physical and mechanical properties [48].

Fibers can be divided into two main parts: natural and synthetics fibers. Natural fibers such as flax, hemp, silk, jute, sisal etc. are used to reinforce matrices, mainly thermoplastics and thermosets. The most popular fiber reinforcements, for their high performance, are carbon and glass fiber. All fibers can be incorporated into a matrix either in continuous or discontinuous lengths as mentioned before. As implied the fibers present different mechanical properties as advantages and disadvantages. Natural fibers are environmentally friendly, renewability of the fibers, good for attenuating the sound, and improved fuel efficiency. On the other hand, synthetic fibers offer high strength, better durability, and moisture resistance properties [48]. In this work, we are going to focused on glass and carbon fibers for their excellent mechanical properties, as mentioned before.

Table 2.5: Matrix desired properties for a composite structure [48].

Matrix must wet the fibers with bonding.
Minimization of moisture absorption
Easily processable into the desired composite shape
Must flow to penetrate the fiber bundles completely and eliminate voids
Must have reasonable strength, modulus and elongation (elongation should be greater than fiber)
Have low shrinkage and coefficient of thermal expansion
Must be elastic to transfer the load to fibers
Have dimensional stability to maintain its shape

Glass Fiber

Glass fiber or fiber glass (GF) consists of fine, flexible glass filaments, fibers drawn or blown directly from glass melt. GF, E-glass, is typically composed of 54% silica, 15% alumina, 16% calcite, 9.5% boron oxide, 5% magnesia, and 0.5% sodium oxide. In Table 2.6, a variety of GF used on the markets are presented. Most common high performance GF are S-Glass, R-Glass and T-Glass. GF is commonly used in composites materials to produced laminated that can be formed into complex shapes for use in automobile and truck bodies, boats, carport roofs, swimming pool covers, sensors, optical communications, and other items requiring light weight, strength, and corrosion resistance [49, 50].

Table 2.6: Density, Tensile strength, Young's modulus and cost of Natural and Synthetic Fibers

Fiber	Density (g/cm^3)	T. Strength (MPa)	Young's Modulus (MPa)	Elongation at brake (%)	Ref.
E-Glass	2.5-2.6	3400-3500	70-75	4.3-4.8	[51, 52]
A-Glass	2.5	2450	70-75		[52, 53]
C-Glass	2.49-2.53	1700-2750	69-70		[50, 53]
D-Glass	2.14-2.16	2500	55	4.5	[53]
S-Glass	2.48-2.5	4600	85-86	5.2	[51, 52]
Carbon Ultra High Modulus	1.78	3400	425	1.4-1.8	[54]
Carbon Ultra High Tenacity	1.78	4800	240	1.4-1.8	[54]

Glass fiber is available in various architectures, as carbon fiber, the most important ones are the continuous fiber and roving, staple fiber and chopped strand mat. Staple fibers, typically from 200 to 400mm long, are excellent for providing bulkiness for filling, filtration and others. Chopped strand consist of fibers chopped from lengths of 3 to 50 mm. Glass fiber mats consists of randomly dispersed chopped fiber or continuous fiber strands held together by a matrix, resin [50]. More examples of the used and markets of Glass fiber are presented on Table 2.7.

Table 2.7: Glass fiber markets and use [50]

Automotive	Wind energy	Aerospace	Marine	Civil construction
External body panels, bumper beams, pultruded body panels and air ducts, engine components, and others.	Typical blades of a wind mill are made of E-glass fiber in an epoxy matrix composite.	For their low elastic modulus GF is more commonly used on secondary parts rather than primary parts examples of this are wings, helicopter rotor blades, engine ducts and others.	Sail boats and hulls and decks of commercial fishing boats and military mine hunters.	Typical applications include the use of glass fibers in polymeric resins for paneling, bathtubs and shower stalls, doors, windows, etc.

Glass fiber market continues to grow. As mentioned by [55, 56] GF and high-performance (HP) GF are expected to grow around 3.9 and 4.7 percent of compound annual growth rate (CAGR) by 2024. HPGF future on markets looks attractive with open opportunities in aerospace and defense, electrical and electronics, pressure vessels, sporting goods, civil engineering, wind energy, automotive, and marine industries. As mentioned by [57] the significant drivers for this market are the growth in automotive production and aircraft deliveries.

Carbon Fiber

Carbon fiber (CF) is made from plastics and materials derived from fossil fuels, as petroleum and coil. CF began to be used commercially in the aerospace industry, aircraft engines, in 1960. CF has been used for vehicle parts, safety products, sports equipment and construction, but the applications of CF are still growing and are expected to represent a crucial role in the daily life products. CF is composed of bonded carbon atoms, in hexagonal patterns, that form long crystals aligned along their lengths. The grids formed by these bounded atoms wrap around to form the walls of long tubes. CF is famous for their different properties such as strength, static and corrosion resistance, heat and electrical conductivity, and others. Specific properties are generally associated with the materials from which the fiber is made. As for example fiber made from coal pitch is generally good at conducting head, but brittle. Fiber made from polyactylonitrile (PAN) has more tension resistance without breaking and is fire resistant. Fiber made from petroleum pith is flexible, but can not stand much pressure [58].

Polymeric matrix

There are three major classes of matrix materials, known as polymeric, metallic and ceramic matrix materials. Most of the composites produced today are based on polymeric matrices, since they have a high compatibility, are low cost, easy to handle, easily processable & have a low density compared to ceramic and metal matrices [59, 60]. Polymeric matrices can be divided according to their thermal behavior as seen on figure 2.6

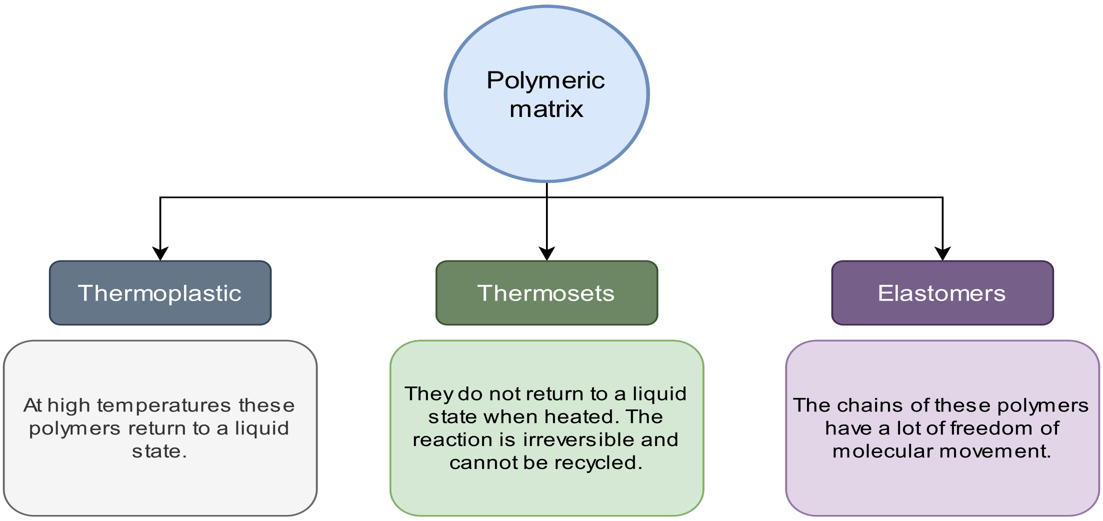


Figure 2.6: Classification scheme of polymeric matrices.

As mentioned before polymeric matrices are the most used on the industries, on this work we will focus on the use of epoxy resins. That is why a briefly explanation about thermosetting and epoxy resins will be presented.

Thermosetting resins

Thermostes are densely cross-linked and have good resistance to heat. Thermoset resin from three dimensional non-reversible networks during the transformation of the liquid to the solid. Thermoset resins transform from liquid to gel and continuation of cured will often transform from gel to glassy material. The resultant solid has good mechanical properties until the T_g [61].

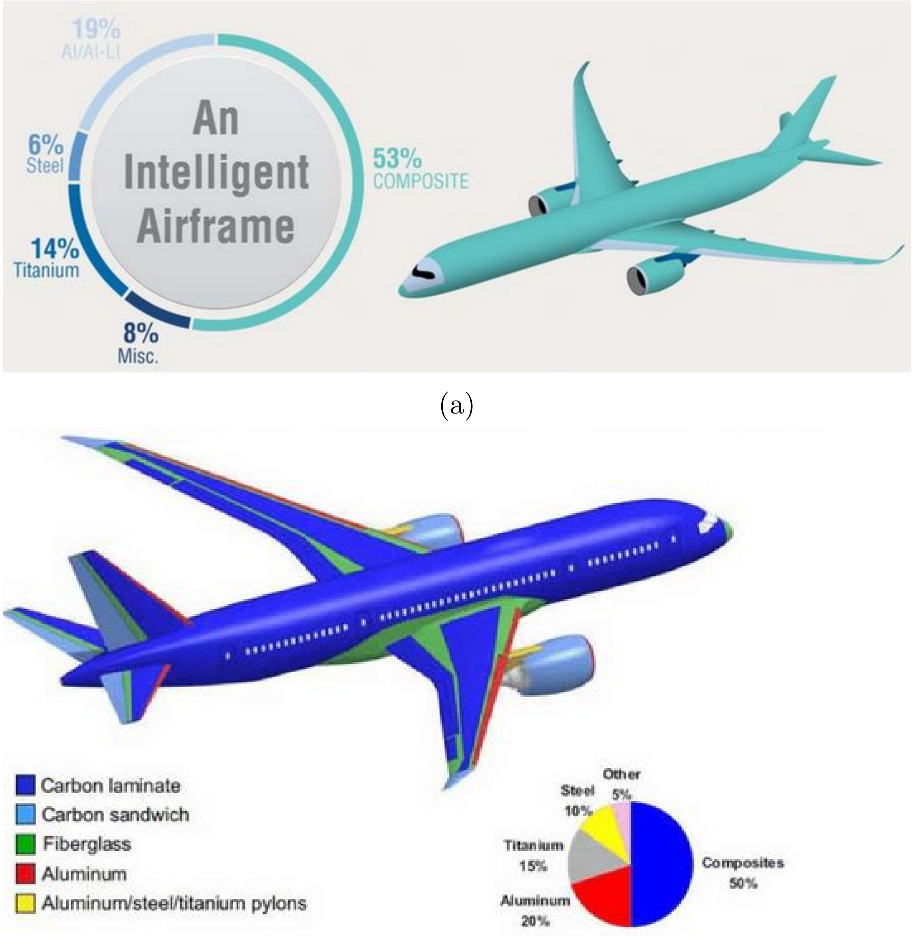
The cure process in thermosets involves chemical reactions transforming reactive monomers into a three-dimensional stable polymer matrix. Cure will usually involve the use of heat, readiation, light, moisture, activators or catalysts. Most common classes of thermosettig polymers are polyesters, epoxies, silicones and others [61].

Epoxy resins

As mentioned before the epoxy resins are one of the most used thermoset resins with a wide range of application fields as electrical, paint & coatings, composites and others. Epoxies are amorphous resins that can be tailored to achieve T_g in a borad range of 60 up to 250^{o}C. Between the advantages that this resins present are high strength, ductility, good adhesive strength, and chemical resistance. However, they are more expensive than most polyester resins [60, 62].

The most commonly used epoxy resin is diglicidyl ether of bisphenol A (DGEBA), that is over the 70 percent of all epoxy usage. The epoxy groups forms coss-links by a condensation mechanism with several harder systems. There is also possible that the epoxies can polymerize by themselves by using a suitable catalyst. Prepregs can also be developed with these resin however the prepregs need to be stored at -18^{o}C to avoid the progression of curing reaction, at this temperature it is possible to store the prepregs for 6 moths [60, 62].

Composite materials account for almost 10 percent of the total value of the epoxy resin market. However this sector is expected to expand as a result of the new generation of lighter, more fuel-efficient aircraft. Examples of this are the Airbus A380 GLARE, and Boeing 787 ”Dream-liner” & the Airbus A350 XWB in where both use composite materials on their fuselage and wings. Figure 2.7 shows the materials used on the Airbus A350 XWB and Boeing 787. that is more than half of the total weight of the aircraft. There are several manufacturing processes to produce composites with epoxy resin, however the most important processes are hand lay up, RTM, filament winding, press molding and vacuum bag autoclave. These process are divided between wet resin and prepreg [62].



(a)

(b)

Figure 2.7: (a) Airbus A350 XWB, and (b) Boeing 787 [63].

2.4 Manufacturing process

As mention before, fiber orientation, structural integrity and fiber volume fraction of textiles are considered essential parameters on FRPs due to engineering requirements as they can affect the efficiency of the transfer load between the fiber and the matrix. That is why it is crucial to consider the manufacturing methods, structure dimensions, fabric architecture, and yarn dimensions according to the piece requirements. Different manufacturing methods and architectures have been developed in Fiber reinforced composites (FRC). Polymer matrix composites are manufactured by various methods that can be classified into two main classifications: open and closed molds. The process can vary from continuous or discontinuous. Most used process are hand lay-up, spray lay-up, filament winding, vacuum bag molding , autoclave molding, injection molding, compression molding, etc [48].

2.4.1 Introduction to open mold processes

The most popular open mold process is hand lay-up. Hand lay-up consists of manually assembled dry plies onto a tool or mold. Plies are then smoothed out to eliminate trapped air and shape the material to the contours of the tool. Dry plies are finally impregnated with a resin. Hand lay up is commonly used to repair structures. Hand lay-up is widely used for their low investment requirements and high flexibility. Disadvantages like labor intensity and high sensitivity to operator techniques [48, 64]. More advantages and disadvantages of this method are presented on Table 2.8. Figure 2.8 shows the Hand lay up process.

Table 2.8: Hand lay up advantages and disadvantages

Advantages	Disadvantages
Low tooling cost	The waste factor can be high in this process
Flexibility design	Low volume process
Sandwich constructions are possible	Only one molded surface is obtained, the other being rough
Semi-skilled workers are needed	Quality of product is related to the skill of the operator
Large and complex items c an be produced	Resins need to be low in viscosity to be workable by hand
Design changes are easily effected	Longer cure times required

Figure 2.8: Hand lay-up Process [65].

Spay Lay-Up process

Process steps are similar to hand lay-up. The spray gun is used to deposit a mixture of fiber resin into the surface of the mold. The spray gun chops the fibers to a determined length and impels them through the resin/catalyst mixture. Resin cure depends on the resin formulation and is done at room temperature. Advantages of this process are: the low tooling cost and suitable for small to medium volume parts. Disadvantages of this process are: Only short fibers are incorporated, which severely limits the mechanical properties of the product. Produced composites tend to be excessively heavy for their high resin concentration [48].

Autoclave molding

Autoclave method is the most common method used in the aerospace industry. In this process, a two-sided mold is used. The lower side is a solid mold, while the upper side is a flexible membrane. Internal components and process diagram is shown in Figure 2.9In most cases, reinforcements are pre-impregnated with resin in the form of prepreg. After the upper mold is installed, a vacuum is applied to the mold cavity. The assembly is placed into an autoclave [48, 66]. Autoclave molding advantages and disadvantages are listed in Table 2.9.

Table 2.9: Autoclave molding advantages and disadvantages [66].

Advantages	Disadvantages
Applied to FR thermosetting and thermoplastic polymer composites.	Low production rate.
Better inter-layer adhesion.	Restriction on component size (depends on the size of the autoclave machine).
Good control of both fiber and resin.	Involvement of skilled labor.
High degree of uniformity in the component.	Expensive technique.
Development of high strength to weight ratio components.	

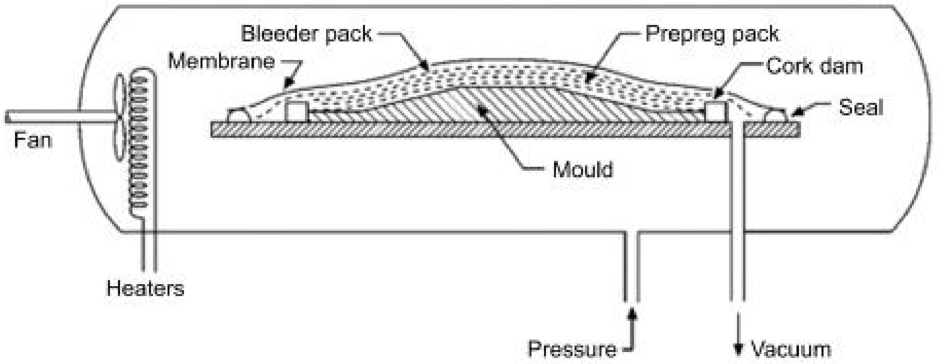


Figure 2.9: Autoclave molding [66].

Wet winding process/Filament winding

Filament winding or wet winding process is the first machine dominated composite structures manufacturing. This process consists of a continuous strands or filaments of fiber that are wound on a supporting form or mandrel. It is generally used to do pipe shaped objects, such as rocket motor cases, high pressure tanks, and launch tubes, it is also used in more commercial products like club shafts and fishing roads [67, 68].

Reinforcement loading can be done by orienting the fibers to match the direction and magnitude of stresses in a structure. The automation of this process assures low labor costs, increases reproducibility, and reduces the scrap rates. Filament winding process consists of fiber roving pulled into a resin bath with liquid resin, catalyst and other ingredients. Fiber guides, located between each creel and the resin bath, are used to control the fiber tension. Excess resin is removed by pulling the resin-impregnated roving across a wiping divide at the end of the resin tank. Finally, an end effector gives the roving orientation to wrap them around the mandrel [67, 68]. The basic diagram of the wet winding process is shown in Figure 2.10.

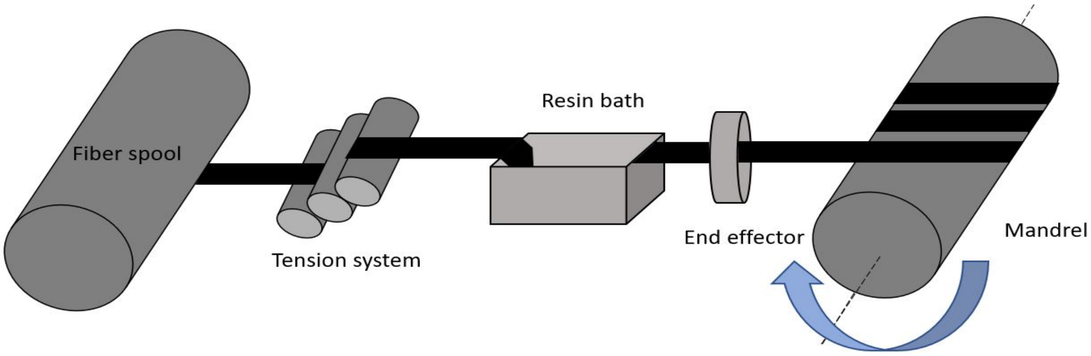


Figure 2.10: Wet winding process.

The most common patterns used in wet winding are polar, helical and hoop winding. Polar winding is used to lay down fiber close to 0 degrees to the longitudinal axis. Pollar windings pass close to the mandrel poles to create a fiber angle close to 0 degrees, to the longitudinal axis. On the other hand, the helical winding is used to place fiber at angles between 5 to 80 degrees to the longitudinal axis, as the polar winding. Fibers are wound in alternating orientations (positive and negative) on the mandrel surface. Resulting in a double layer of wound material. Hoop winding, a variation of the helical winding, is used to deposit fiber on angles close to 90 degrees to the longitudinal axis. Hoop winding is usually applied to the cylindrical portion of a mandrel. Resulting in a single layer reinforcement material [68]. For a graphical view of the different patterns, please saw Figure .

2.4.2 Closed molding processes

Compared to open molding processes closed molding process enable manufacturers to develop better parts faster and more consistently. The advantages that we can find in closed molding process are better finished parts, less waste and low post work required. These molding process are usually more expensive. Close molding methods can vary from vacuum bagging, vacuum infusion processing, compression molding, resin transfer molding and Vacuum resin transfer molding (RTM and VaRTM) and others. Table 2.10 shows different process uses for 3D woven composites.

Injection molding

The injection molding process involves in forcing/injecting a fluid plastic material into a closed mold of the desired shape. The molding compound is fed into the injection chamber through the feed hopper. In the injection chamber, the molding compound is heated, wherein it changes into liquid form. It is then forced into the injection mold by the plunger as shown in Figure 2.11. The material solidifies in the mold and can be removed from the mold after solidification. This method is

Table 2.10: Manufacturing process of 3D woven composites

Material	Structure	MFG Process	MFG parameters	Properties	Ref.
Carbon fiber	LTL-PW, LTL-TW & LTL-SW	RTM	P-0.2 for 30 min, Post cure for 1 hour at 80°	LTL-PW EM-41.25±1.49, TS-335.26±15.24 LTL-TW EM-44.2±0.98, TS-359.56±22.45 LTL-SW EM-51.52±9.56, TS-345.47±15.8	[69]
Carbon Fiber	3D ORT, AI, multi-layer plain	RTM	5-layers preform, P-0.2 for 15 min, Post cure for 1 hour at 80°		[70]
Glass, Carbon, Polyethylene fiber with epoxy–vinylester resin	Orthogonal with an asymmetric distribution	Vacuum infusion		EM-F-38.4±1.6 EM-W-24.6±.7 TS-F-531±42 TS-W-395±35	[71]

F - Fill direction
W - Warp direction
EM - Elastic Modulus (GPa)
TS - Tensile Strength (MPa)
P - Pressure (MPa)

usually used for high-volume and low cost manufacturing. The process is limited to materials with short fibers [48].

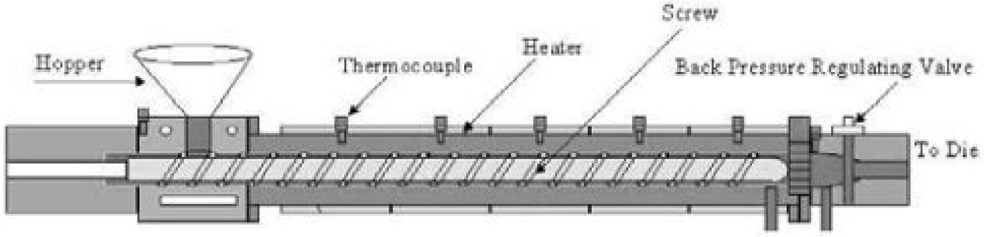


Figure 2.11: Injection molding [48].

Vacuum Bag Molding

It is considered an extension of the wet lay-up process. In this process, pressure is applied to the laminate once laid up to improve its consolidation. This process uses a flexible bag that allows the evacuation of air from the composite by applying atmospheric pressure. A vacuum pump which extracts the air helps to eliminate entrapped air. The bag has to fold objectives: provides a means for removing volatile products during cure and improves a means for the application of one atmosphere pressure. This process is commonly used to produce race-cars and boat components [48]. Vacuum bagging process is shown on Figure 2.12.

Resin transfer molding (RTM and VaRTM)

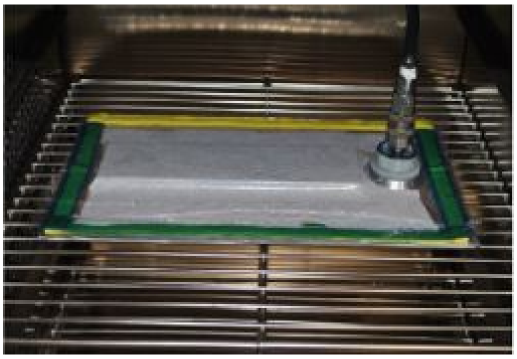
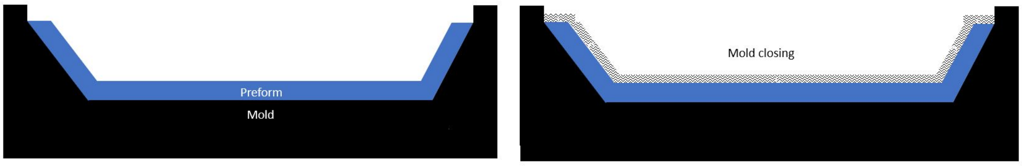


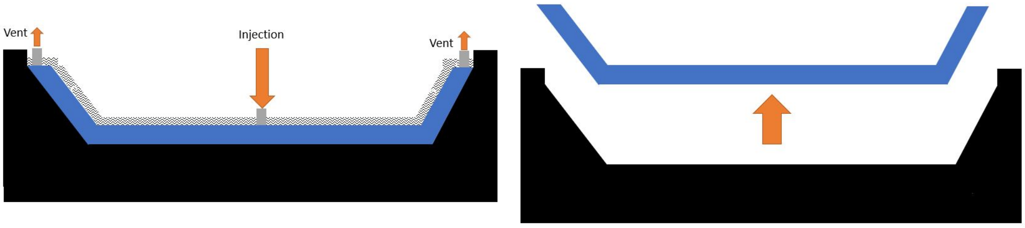
Figure 2.12: Vacuum Bag Molding [65].

RTM consists in injecting resin under pressure into a mold cavity. The complete process is made by stacking dry fabrics and held together using clamps or a press. Resin is then injected under pressure and flows through and impregnates the fabric. It can be used for stitched and woven fabrics, although stitch fabrics facilitate the resin flow. The process is dependent on the pressure gradient in the tool, the viscosity of the resin, and the architecture and nature of the fabric, permeability. Finally, the composite is allowed to cure once the fabric has completely wet out, this can happen at room temperature or elevated temperatures. This process is known for producing composites with low void content, high fiber content, and high mechanical properties. Some disadvantages of RTM process are the expensive tooling and the complexity of tooling design for large and complex parts. To improve cycle times and part quality and properties, number of variations of RTM have been developed as VaRTM and high-pressure RTM which add complexity and are more expensive despite their advantages [72, 73].Basic process diagram is shown on Figure 2.13 which consists on the sample preparation 2.13a, sealing 2.13b, injection 2.13c and final part 2.13d.



(a) Sample preparation

(b) Sealing



(c) Injection

(d) Final part

Figure 2.13: RTM process: (*a*) Sample preparation, (*b*) Mold closing/sealing, (*c*) Injection, (*d*) Final part.

VaRTM as mention before works, as a variation of RTM process to reduce cost and design difficulties associated with extensive metal tools. In VaRTM the upper side of the mold is made from flexible material as silicon or nylon. Disadvantages found in this process are high void content and inherent thickness that limit the effective structural stress transferring between fibers. Excess of resin on vacuum infusion processes causes an uncontrollable fiber volume fraction, lower mechanical properties and varying laminate thickness; This can be produced by pressurizing the resin feeder above the atmospheric pressure or by a high volume inside the bag. Some studies also suggested applying external compaction pressure as the inflatable bladder, permanent magnets or pressurized air to reduce void and increase fiber volume fraction. Limitations of clamping forces on this process limit the used of compaction pressure to only small-medium size components [73]. Other Vacuum infusion variation processes have been developed by the private sector to improve cycle times and reduce void content as Double Bag Vacuum Infusion (DBVI), Vacuum Assisted Process (VAP), and Controlled Atmospheric Pressure Resin Infusion (CAPRI). However, as mention in [73] the benefit of these processes remains unclear and further investigation is needed. A mold preparation example of RTM is shown on Figure 2.14.

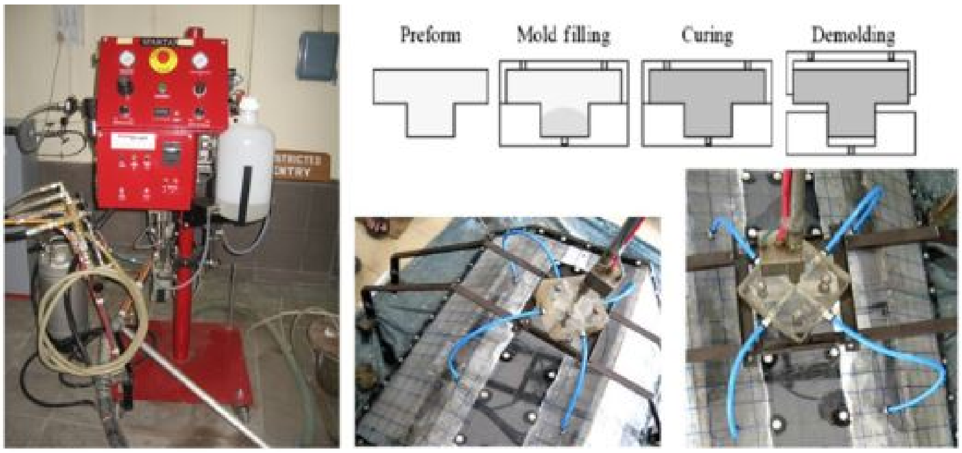


Figure 2.14: Resin transfer molding [65].

Compression Molding

Compression molding is one of the oldest manufacturing techniques and is typically used to manufacture of a small to medium randomly aligned fiber reinforced composite. Compression molding can provide better physical and mechanical properties compared to the injection molding process. Components are produced by placing a measured charge of preheated material into a cavity of a heated matching tool set. Bulk and sheet molding compounds (BMC & SMC) are usually processed using compression molding by a hydraulic press that closes the mold and makes the material flows throughout the cavity. The curing process takes place while the heated mold tool is clamped. Compression molded SMC components can be used to replace metal stamping in several different automotive applications. Products lose some degree of complexity. This process has a high tooling cost and is not practical for low volume production. It is also essential to control the cure time, otherwise cracking, blistering or warping may occur. Other variants of this process can be used as over-molding [48, 72]. Basic diagram of compression molding is shown in Figure 2.15.

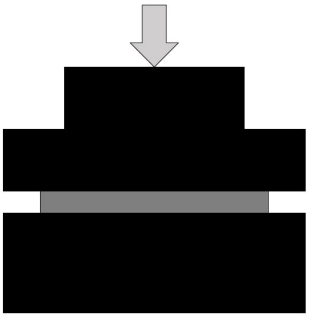


Figure 2.15: Compression molding.

The compression molding process is commonly used for the fabrication of unidirectional and 2D laminates FRP composites. Even though compression molding has proved outstanding mechanical properties.

2.4.3 Forged composite/Randomly oriented strands fabrics

Compression molding can be also used with randomly oriented strands (ROS) that are long discontinuous fibre systems that exhibit excellent formability characteristics and stiffness properties similar to quasi-isotropic laminates. The basic process consists of UD strands that are later chopped and then randomly distributed into a mat and sandwiched between two resin layers. Material is then compacted into rollers giving the sheet form which would be later used on a compression molding process as shown in the Figure 2.16. The main advantages of this process are the reduction time on the manufacturing, enables complex structures and weight saving as mentioned by Feraboli [74, 75]. ROS can also present a wide variation on modulus and strength throughout the composite that might need further study as the material differs from regular composites mentioned by Nicoletto et al [76].

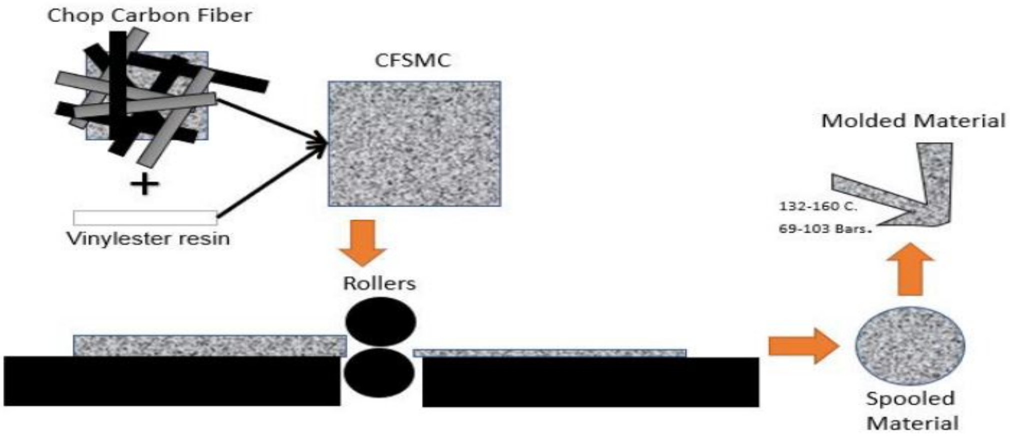


Figure 2.16: Randomly oriented process (ROS) manufacturing.

Table 2.11: Reported mechanical properties of different MFG processes

MFG process	Structure	Mechanical properties	Ref.
VaRTM	Carbon/Basalt plain woven fabrics (10 plies)	Carbon F. FS-860.92 FM-54.17 Basalt F. FS-428.05 FM-25.37	[77]
Compression molding	Basalt plain fabric (10 layers)	TS-240 TM-15.92 FS-273.9 FM-8.11	[78]
Compression molding	SMC and UD prepregs	SMC FM-33.1	[79]
VaRTM	Carbon (2x2 twill) /Glass(PW)/Basalt Fiber(PW) (20 plies)	Glass F. ILSS-59.7	[80]
Hand lay-up	Basalt plain weave fabric	Glass F. TS-180.3 IS-1.483	[81]
CF-ROS		TM_{57CF}-36 TS_{57CF}-185 TM_{53CF}-34 TS_{53CF}-189	[76]
RTM	Basal/Aramid plain weave fabrics (13 layers)	Basalt F. FS-229.34 FM-14.35 Aramid F. FS-219.37 FM-17.57	[82]
Compression molding	Chopped Carbon fiber	High CM 18mm tape TS-400 Low CM 18mm tape TS-230	[83]

TM - Tensile Modulus (GPa)	TS - Tensile Strength (MPa)
FM - Flexural Modulus (GPa)	FS - Flexural Strength (MPa)
IS - Impact Strength (J/mm)	ILSS - Interlaminar Shear Strength (MPa)

2.5 Composites joint

The bonding process of composites materials is an important aspect that is challenging different markets to use this material in different application areas like the automotive and the aerospace industry. Different assembly methods of composites materials have been used like mechanical fixing, ultrasonic welding, structural adhesives, and acrylic tapes. Bonded or bolted joints are applied to transmit the loads between the components of the structure. [84]. Figure 2.17 shows different examples of bonding in composite materials.

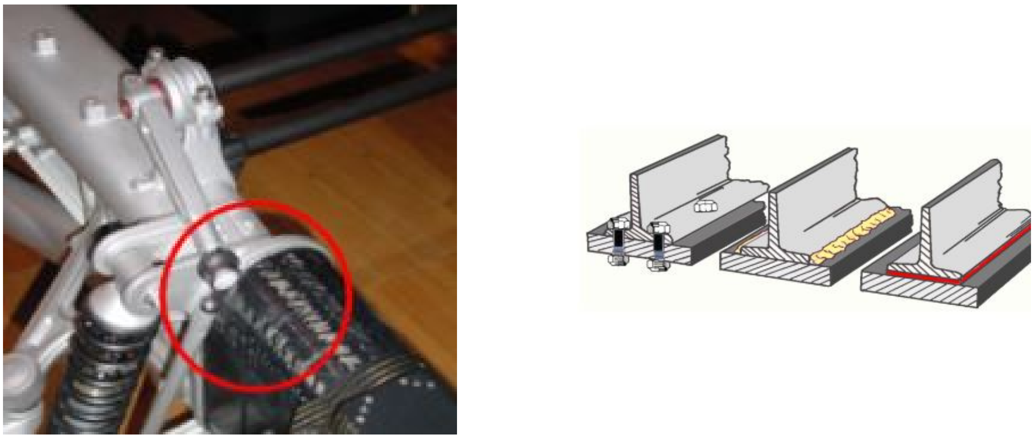


Figure 2.17: Bonding composite materials.

Bolted joints are the main form of load transfer between structural parts, compared to other bonding methods, mechanical fastening is more reliable and has the potential to improve structural efficiency. However, bolted joints are a source of stress concentration and may cause structural failures if they are designed improperly. Important parameters in the bolted joints design are the geometry, and the material properties of the bolted, size and arrangement of the fasteners, the fastener material properties, etc. The design of bolted joints in composite structures is restricted in the developed analytical tools [85]. Examples of bolt joints are shown in Fig. 2.18.

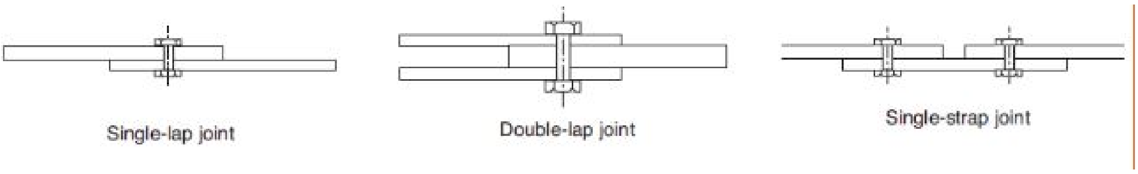


Figure 2.18: Bolt joints 2.18.

Traditional bonding has presented several challenges to the development of composite materials, as the required drilling or work of the material can affect the material's resistance causing an early failure. In recent years, adhesive bonding has become an attractive option to use with composite materials, as this type of joint can be used to avoid the local increase of stress and minimize the risk of failure on the structure. Three types of joints are possible: bolt joints, adhesive bonding joints, and hybrid joints [84, 86].

Advantages of adhesive bonding joints are their capability to provide flexibility, fatigue & impact resistance while reducing noise and absorbing vibrations. The joint is generally realized on the intern face of the composite, avoiding structural damages to the material and a better aesthetic look [84]. Types of adhesive joints are shown in Fig 2.19. The adhesive bonding joint process can be classified in:

- Glued to frame.
- Bonding of stiffeners and moldings.
- Bonding of the composite material throughout the surface.
- Unions of small parts.

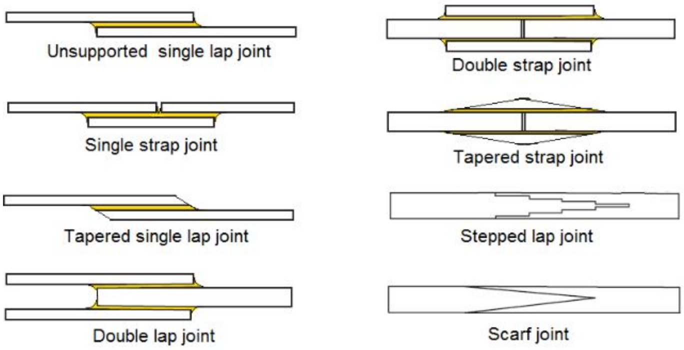
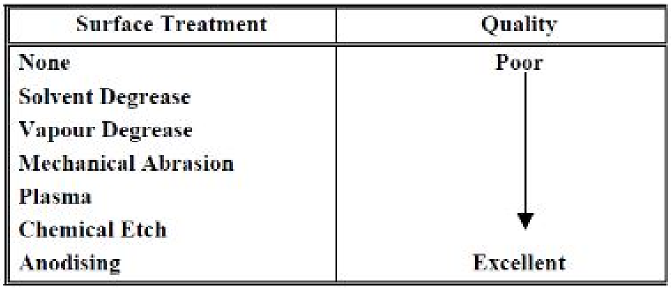


Figure 2.19: Adhesive joints type 2.19.

Characterization of the joint adhesive compatibility with the composite and the other material is required, as well as the mechanical behavior of the joint and its resistance. The most important performance requirements for composite bonding adhesives are durability/fatigue, overlap shear, and flexibility. Resistance of the bonding is related to the overlap length, end effect, and bond effect. Other important parameters to consider are surface preparation, the selection of a proper surface treatment that influences the resistance, and the durability of the joint. Surface preparation helps to remove contaminants increase wet-ability and promotes micro-mechanical interlocking [84, 86]. Figure 2.20 shows the quality of different surface preparation methods.



Surface Treatment	Quality
None	Poor
Solvent Degrease	
Vapour Degrease	
Mechanical Abrasion	
Plasma	
Chemical Etch	
Anodising	Excellent

Figure 2.20: Surface preparation methods 2.20.

2.6 Fiber reinforced plastics (FRPs)

As mention before, the mechanical properties are one of the most crucial aspects of FRP composites. In which the reinforcement takes the main role to determine the properties of the material. As mention before, the fibers carry the loads along with their longitudinal directions while the matrix transfers stresses between the reinforcing fibers and protects the fiber from mechanical and/or environmental damages. The fiber reinforce plastics, also known as polymer matrix composites are very popular for their low cost, simple fraction methods, lightweight and desirable mechanical properties. Numerous applications have been found and have keep growing in recent years. The properties of these materials depends on the fiber properties, orientation & concentration and polymer matrix properties [48].

When the material is combined, the properties of the composite differ from the original ones. To understand the composite properties is vital to develop the micromechanical analysis and experimental data of the composite. As explained before, the fiber structures change the properties of the material. As for example, unidirectional lamina properties will vary according to how the stress is subjected to the specimen as we have an anisotropic material [87].

2.6.1 Mechanical properties of FRP composites (FRPCs)

For FRP composites, mechanical properties are one of the most critical aspects as the reinforcement affects the mechanical properties of the FRPCs as mentioned before. The most popular mechanical properties considered and studied are tensile, bending, impact strength and hardness. These properties depend on the fibers and matrix [48]. Table 2.11 shows different manufacturing processes and mechanical properties reported in the literature.

The rule of mixture gives the strength of unidirectional reinforced composites, in the direction of the fiber:

$$\sigma_f \ \mathrm{V}_f + \sigma_m(1\text{-}\mathrm{V}_f) \tag{2.1}$$

Where V_f is the volume fraction of fibers, σ_f is the tensile strength of fibers and σ_m is the stress developed in the matrix. For composites with long parallel fibers the Young modulus (E_c) in the fiber direction is calculated:

$$E_c = \mathrm{E}_f\mathrm{V}_f + \mathrm{E}_m\mathrm{V}_m \tag{2.2}$$

where E_c, E_f, E_m are the elastic modulus of the composite, fiber and matrix respectively and V_f and V_m are the fiber and matrix volume fractions respectively.

Tensile strength (TS), measure in the unit of force per unit area, is the maximum stress that a material can withstand without failure. Tensile properties of FRPCs can be determined according to the ASTM D638 [48]. TS of FRPCs is determined by the following equation:

$$\sigma_f u = \mathrm{F}_u \ / \ A_f \tag{2.3}$$

where, F_u is the load at failure, A_f is the average filament cross sectional area.

The material's ability to resist deformation under load is known as bending or flexural strength. The flexural strength represents the highest stress experienced within the material at its moment of rupture. Two methods can be used to determine the bending/flexural properties of a material: three-point and four point loading system. Tree-point loading is included in ASTM 790 while four-point loading is in ASTM D 6272 [48]. For a rectangular sample under a load in a three-point bending setup, the bending strength is calculated by:

$$\sigma = \mathrm{3FL} \ / \ \mathrm{2bd}^2 \tag{2.4}$$

where F is the load, L is the length of the support span, b is width and d is thickness. For a rectangular sample under a load in a four-point bending setup where the loading span is one-third of the support span, bending strength is calculated by:

$$\sigma = \mathrm{FL} \ / \ \mathrm{bd}^2 \tag{2.5}$$

where F, L, b, and d have the same meaning as described before.

Impact strength is the ability of a material to resist a suddenly applied load. The impact test of FRPCs is usually carried by two different types of testing: Charpy test and Izod test. Izod impact strength of FRPCs can be determined according to ASTM D256 while the Charpy impact strength can be determined according to ASTM D 6110 [48].

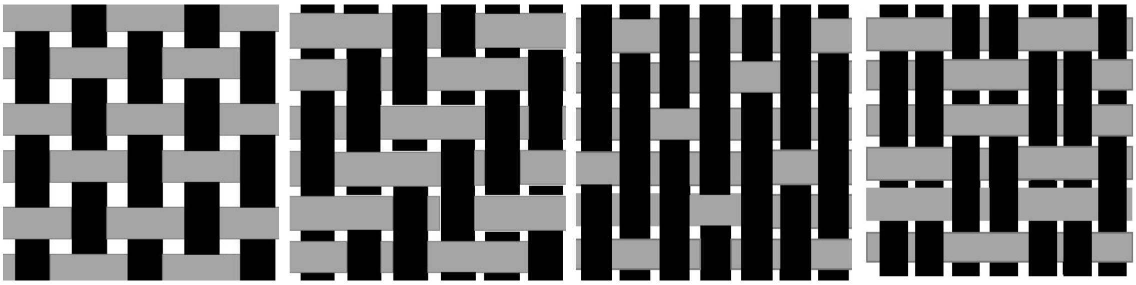
Mechanical properties of different FRPCs are studied by many researchers. Manuneethi et al, studied the impact properties for glass and hybrid, glass/jute fiber by hand layup and VaRTM [88] in wich VaRTM shows an increase impact response of 2.5 to 4 percent compared to hand lay-up process that is related to high fiber matrix bonding and low void content. Taniguchi et al, studied the effects of the strain rate of GFRPs. In which they found a dependence between the strain rate, and the tensile strength and fracture strain. It was also found a correlation between the strain rate was strongly affected bu the fiber diameter [89].

Effects of hybrid composites (Glass/Carbon fiber) on the interlaminar shear strength (ILSS) were studied by Turla et al, in which improved ILLS properties were found compared to glass FRCs and carbon FRCs [90].

Table 2.12: Manufacturing process of FRPCs

Material	Fiber orientation	MFG Process	MFG parameters	Properties	Ref.
Jute$_{40}$/Glass$_{60}$ Fiber	Plain weave 10 layers	Hand lay-up		TS-125 FS-160 EM-12.5 FM-12.5	[91]
Glass Fiber, Glass/Jute fiber	[45g/0g/90g/-45g]$_8$	Hand lay-up, VaRTM	P -0.17		[88]
Glass Fiber/Epoxy resin	SMC 3 layers	Compression molding	P-0.4 T-100°C	TS-240 FS-320 FM-14 EM-17	[92]
Glass and Basalt Fiber	SMC (Chopped) 3 layers	Compression molding	P-.124 T-100°C for 1h	Glass F. EM-6.2 TS-70 Basalt EM-7.1 TS-60	[93]
Glass Fiber	SMC			TS-95 FS-135 EM-6.6 FM-5.5	[94]
Bamboo$_{25}$/Glass Fiber$_{75}$	BMC Laminates	Compression Molding	P-4.9 T-140°C	EM-37 FS-140	[95]
Basalt/Glass fiber	SMC 6 layers	Vacuum bag	Cured at room temperature	Glass F. EM-8.28 TS-145.4 BGF 1-6 EM-14.1 TS-210.3	[40]
Recycle Carbon Fiber	SMC (Chopped)	Compression molding	P-0.22 T-145°C for 3min	FS-120 FM-12	[96]

F - Fill direction
EM - Elastic Modulus (GPa)
FM - Flexural Modulus (GPa)
P - Pressure (MPa)
W - Warp direction
TS - Tensile Strength (MPa)
FS - Flexural Strength (MPa)



(a) Plain weave (b) Twill weave (c) Stain weave (d) Basket weave

Figure 2.21: Fabric patters: (*a*) Plain, (*b*) Twill, (*c*) Stain, (*d*) Basket weaves.

2.6.2 Damage classification

Damage mechanisms in composites have proven to be more complex than common materials as metals. Defects can happen in the composite material or structure during the manufacturing process or during its service life. The three major typed of damages in CFRPs under loading conditions are Fiber breakage, cross ply crack within fiber plies and delamination. Fiber breakage cause fiber to lose their stress capabilities and transfer loads to the unbroken fiber. Cross ply crack is due to matrix structural damage due to the strength of the fibers being considerably higher. Delamination is due to the separation of the fiber plies, this may be caused by matrix cracking between the layers and debonding at the fiber-matrix interface [97, 98].

2.7 Woven Fabric history

Historically weaving developed among many cultures simultaneously. Evolving into an art early on. With the increase of weaving over time woven tapestries began to appear in different regions such as Egypt, Greece, and Rome in which they depicted heroes and other legends. Later European tapestries France, Belgium, and other countries illustrated religious themes and biblical stories. Weaving continued evolving and with time humans stopped using fingers as the first looms. During the Neolithic period, longer sticks and poles replaced fingers. These sticks formed a primitive loom referred to as a “horizontal ground loom.” Early looms needed one or two persons to work on them. Different horizontal and vertical looms began to appear in different areas as Asia, Africa and Europe [17, 99]. With the invention of the frame loom and treadle the process became easier, that lead to the increased in production. By the eleventh century, the first weaving guilds were formed in Europe. Craftspeople wove fine cloth of silk, linen, and wool in many patterns that are still used today [100]. Figure 2.21 shows examples of 2D textile patterns.

Industrial Revolution set the development of new designs of looms which allowed greater speeds, larger warps, and more complex patterns. John kay for example invented the flying shuttle and in 1803 Jacquard loom was invented as the first programmable loom. The many mathematical and computational techniques have continued to evolve with these technologies, including differential equations, numerical methods, image processing, pattern recognition, and statics. Other tools like computer-aided design (CAD) and computer-aided looms (CAL) also widespread with these technological advances [100, 17, 99].

Nowadays technical textiles began to appear in different engineering areas in which the search for technical performance and functional properties are more important than their cultural impact, differing as how they were used in early history. Technical/structural textiles consist of a manufactured assembly of fibers, yarns and/or strips with sufficient cohesion to accomplish the needed mechanical properties [101].

Textile structural composites are widely used as they have shown better specific properties than basic materials like metal and ceramics. Textile structures present less delamination problems than other composites and are damage tolerant, appearing as a good alternative to different components. From a textile processing viewpoint, they are readily available, cheap and not labor intensive. Textiles fabrication is done by weaving, braiding, knitting, stitching, and by using nonwoven techniques. These techniques can vary according to the user requirements [102, 101]. FRP can be categorized in different manners according to how the fabric is developed, between them we have unidirectional FRP (UD-FRP), non-crimp fabrics (NCFs), chopped fiber, 2D woven reinforce plastics (2D-RP), and 3D woven reinforced plastics (3D-RP). FRP textiles can be divided in two principal areas 2D and 3D FRP plastic composites.

2.7.1 2D woven fabrics

Woven fabrics are made of two sets of yarns that are interlaced at right angles to each other. The yarns that rin along the length of the fabric are known as warp yarns, while the yarns which run from one side to the other are known as the wefts. It is important to mention that in triaxial and three-dimensional fabrics arrangement can differ. As mention before woven textiles are designed to meet technical requirements as strength, thickness, extensibility, porosity and durability that can vary according to the end use. Textiles properties can change depending on the direction in which they are measured as for example in the wrap and weft directions [101].

2D woven laminated composites

2D woven fabrics were popular for being flexible, warmth-keeping and strong. For these reasons they were suitable to be used as materials for clothing and other domestic uses. High performance fibers, like fiber glass and carbon, began to expand finding many technical applications like textile composite reinforcements for different areas as civil & agricultural engineering, aeronautics & automotive, and protection & defense [103, 104].

2D woven laminated composites are characterized by their high in-plane specific stiffness and strength producing a high quality product, but with limitations for the application of real-life products that could be subjected to out-of-plane loads. Examples of this applications are wind turbine blades, stringers and pressure vessels. The most common failure mode experimented for this materials is delamination which is produce from cracks on the matrix materials that spread quickly along the resin-rich areas (RRA) between the layers. These cracks can be form due to residual stresses, edge damage during cutting and out of plan impacts. Their poor impact resistance and low delamination strength can also be explained by their lack of binder fiber (Z-fibers) [105, 102, 106].

Examples of 2D woven fabrics can be found on automobile bodies and surfboards, that are typically made from FG woven materials bounded with plastic or resin. On the other hand, carbon fiber haven been used in more advanced composites than others for their ability to create lighter and stronger materials. Carbon composites are often found in golf clubs and other sporting equipment's, they are also used on the disc brake pads on cars with a carbon matrix and a silica reinforcement [18]. Some examples of woven patterns are shown on Figure 2.21.Other patterns and fiber configurations can be found on the market as 4x4 Twill Weave, 4, 5 and 8 Harness-Satin as some examples [107].

Biaxial fabrics

2D biaxial woven composites are popular for their high in-plane properties compared to the 3d woven composites due to the absence of z-yarns and high directional volume fraction. Biaxial woven composites also shown consistent dry fabric properties and good drapability, is the most economical structure in the composite structures and is produced with a highly automated process. As other 2D woven composites, braided materials has low out-of-plane properties [60].

Triaxial fabrics

Triaxial fabrics woven technique vary as common 2D woven structures, which have two sets of warp yarns that are generally inserted at 60°to the weft. Other variations of these fabrics like tetra-axial fabric can be found which has four sets of yarns that are inclined at 45°to each other. Triaxial fabrics are defined as cloth in which the three sets of threads form a multitude of equilateral triangles forming a more stable construction. Resulting in an equal strength in all directions. In the basic triaxial fabric, the warp travels from selvedge to selvedge at an angle of 30°from the vertical. When a warp yarn reaches the selvedge, it is turned through and angle of 120°and travels to the opposite selvedge. Weft yarns are inserted at right angles to the selvedge. Figure 2.22 shows the basic triaxial fabric which forms a diamond shape at the center. These helps to produce superior tear, bursting and shear resistance on the material. The standard weave can be modified by having biplane, stuffed or basic basket weaves. These fabrics have a wide range of technical applications that can vary from tire fabrics, pressure receptacles, laminated structures and others [108].

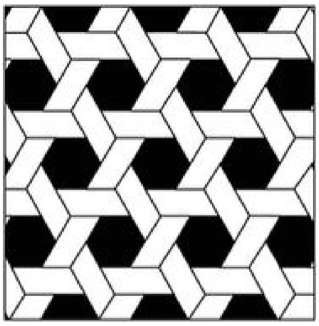


Figure 2.22: Basic triaxial fabric weave [108].

2.7.2 3D FRP composites

3D FRP composites have been developed in recent years driven for the reduction of fabrication cost, increase of through-thickness mechanical properties and improve impact damage tolerance. 3D composites are made using the textile processing techniques of weaving, knitting, braiding, stitching and z-spinning. Braiding was the first technology used for 3D composites in the aerospace industry, specifically to replace high temperature metallic alloys in rocket motor components to reduce weight at 30-50%. 3D composites appeared shortly afterwards to developed brake components for a jet aircraft, they were used to replace high-temperature metal alloys to improve durability and reduce heat distribution. 3D composites at this point were made primarily of carbon-carbon materials [109]. Examples of 3D woven composites are shown in Figure 2.23.

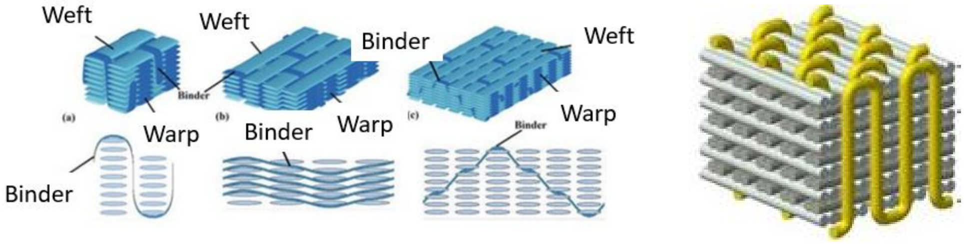


Figure 2.23: 3D FRP Composites (a) 3D woven fabric[102], (b) Non crimp fabric[110].

2.7.3 3D woven composites

3D woven composites are made from woven textile reinforcement with yarns orientated along the x-axis, y-axis and the z-axis. As in 2D woven composites weft and warp yarns run across the X and Y axis respectively, while binders run across the Z axis. In comparison with 2D woven composites they present better flexure, impact and in & out-laminar properties. It can also be used with textile technology to manufacture near-net-shape preforms, to reduce the manufacturing time [105, 111]. Other benefits found on 3D woven composites are shown in Table 2.13.

Table 2.13: 3D woven structure composites advantages

Benefits
Good damage tolerance, toughness and delamination resistance of 3D woven composite structures
Elimination of labor intensive manual ply lay-up
Easy wet-out of thick 3D woven structures relative to traditional laminate structures of comparable thickness and fiber volume

3D woven composites can be classified into through-the-thickness (TT) when the binder penetrates all the fabric and layer-to-layer when the binder only holds adjacent layers. This classification can be expanded according to the interlacing angle of the structure. For example, the angle interlock (AI) in which the interlacing angle, the angle between the warp and weft yarns, can have any value except 90°. And Orthogonal interlock (ORT) occurs occurs when the interlacing angle between the binder and weft yarns is equal to 90°[105]. Figure 2.24 shows basic diagram of the weaving patterns.

Table 2.14: Work done on 3D woven composites

Material	Structure	Comments	Ref.
Carbon Fiber & Steel/copper filaments	Orthogonal through-the-thickness	Use of steel Z filament	[112]
Carbon Fiber	Orthogonal / angle interlock	Tensile, compressive and flexural behavior	[113]
Glass, Carbon, Polyethylene fiber with epoxy–vinylester resin	Orthogonal with an asymmetric distribution	Ballistic performance	[114]
Carbon Fiber	Orthogonal through-the-thickness	16 warp, 16 vertical weft and two horizontal weft yarns	[115]
Carbon fiber	Orthogonal through-the-thickness	Load cases of in-plane tension/compression and out of plane bending	[116]
Basalt/aramid	Orthogonal	6 warp and 7 weft	[117]

Several studies have been developed to understand how does these materials behaves and the different impacts that the architectures and their variations can produced to the material. Stig et al studied the in plane and out plane properties of 2D and 3D woven composites in which they found that 3D woven composites presents higher out of plane properties than 2D laminates. While the in plane stiffness and strength were found to be lower [115]. Abbasi et al studied the 3D woven composites response using metal Z-filaments that increases the decontamination resistance of mode of failure I by 50 times [112]. A list of works is on 3D woven composites is presented on Table 2.14.

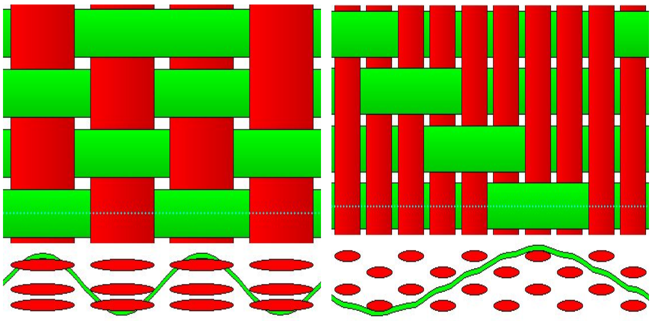

(a) Orthogonal (b) Angle interlock

Figure 2.24: 3D woven architectures made by TexGen.

Applications of 3D woven composites have been growing at a high rate in recent years. An example of this is the automotive industry in which 3D carbon fiber woven structures have been used on the development of a floor section [69]. The aerospace industry have began using 3D woven composites (ORT structure) and they can be found on the LEAP engine´s fan blades which safe around 226kg weight per engine.

Right now they are commercially used in the Airbus A320neo, Boeing 737 MAX and the COMAC C919 [118].

Non-crimp fabrics (NCFs)

Multi non crimp fabrics consist of multiple yarn bands, bans are laid on top of each in different angles. Fabrics can be classified in three main types; uni-axial, bi-axial and multi-axial NCFs. As their names implied on UNCFs fibers are oriented in one direction, BNCFS fibers are oriented in two directions and on MNCFs fibers are oriented in more than two directions. NCFs are used for composite applications due to the straight orientation of the yarns and the possibility to arrange the yarns in several narrowly adjustable directions. Fiber bands are oriented on function of the fabrics requirements for its application [20].

Some advantages that NCFs presents in high-performance materials are a perfectly straight bundle that ensures good in-plane properties and a high degree of freedom on the fiber orientation. Fibers can in up to seven different orientations (0°, 90°, +θ and -θ, with θ between 25°and 65°) [21, 106, 119]. Some factors that may alter the fabric properties are the spacing between consecutive rows of stitching, length of a stitch, stitching tension, yarn size and stitching direction that may cause openings and/or channels [21]. Stitching advantages and disadvantages are presented on Table 2.15.

Table 2.15: Stitching advantages and disadvantages

Advantages	Disadvantages
Openings and channels improve the permeability of fabrics	Fibers can slightly pushed aside causing waviness which can affect the mechanical properties of the composite
Open spaces in the textile, openings and channels, facilitates the shear process and therefore allows for larger fabric deformations	Fibres may also be slightly damaged
Stitched composite helped to divide the load among the layers	Openings may cause RRA

NCFs manufacturing consists on placing ravings at a multi non-crimp machine that will define angles. First the lowest layer is produced and additional layers are placed on top of the first one according the the fabric to manufacture. after all layers are positioned, the warp-knitting unit combines the layers with additional warp yarns As shown on Figure . Several different stitching patterns can be created, depending on the desired fabric properties and fibre orientations. Most common stitching patterns are tricot, chain, tricot-chain and diamond stitching [20, 21].

Chapter 3

Experimental Methodology

3.1 Introduction

Fiber reinforced Plastics (FRPs) composites production and relevance have grown significantly on the past decades. Different industries like the aerospace, automotive and sports began to use this materials because of the outstanding properties they have like good fatigue resistance, good corrosion & impact resistance, good mechanical properties, low density, high rigid per unit area and others; All this makes FRPs composites perfect for different engineering applications, that is why it is important to understand how these materials work and behave [18, 23, 32, 33].

While FRP has been increasing different variations and architectures have appeared like technical textiles, consisting of a manufacturing assembly of fiber yarns to accomplish different manufacturing properties. Composite materials made by technical textiles can be divided onto 2D and 3D composites [101]. Different variations of technical textiles have been used in the present past within the known advantages of 2D weaving, we have their good flexibility and in plane mechanical properties, but lack delamination resistance affecting the durability and strength of the product. Examples of 2D weavings are plain, twill, 4 hardness-stain and others.

3D weaving composites, on the other hand have proven outstanding out of plane mechanical properties and fatigue resistance compared to 2D laminates, but also presented lower in-plane properties. 3D weaving composites can be classified as orthogonal, layer to layer and angle interlock structures [103, 115, 120]. 3D weaving composites have shown different mechanical properties according to the use architecture. As for example angle interlock architectures have shown better tensile strength properties than others as reported by [113, 121]. However, further studies are required to understand how the 3D woven architectures manufacturing affects material properties as most of these materials were produced by infusion processes like RTM and VaRTM.

This study aimed to understand how does mechanical properties of 3D woven composites can be improved by a compression molding process that helps to minimize the crimp effect on 3D woven composites. 2D woven glass fibers were developed for comparison and to refine the manufacturing process, with the purpose to understand the details that could be presented when manufacturing carbon fiber. Both carbon and glass fiber composites, were developed with a low viscosity resin and a higher viscosity resin to understand how does this viscosity affects the impregnation process of the composite on the different manufacturing processes. Diagram

3.1 shows the steps developed to produce both 2D and 3D weaving specimens for tensile and flexion tests.

The thesis consists mainly of 3 stages:

- Evaluate the manufacturing processes with which the best mechanical properties are obtained on 2D glass fiber composites.
- Evaluate the manufacturing processes with which the best mechanical properties are obtained on 3D carbon fiber composites.
- Evaluate the effects of temperature and compaction on the mechanical properties of the different manufacturing processes on 3D carbon fiber composites.

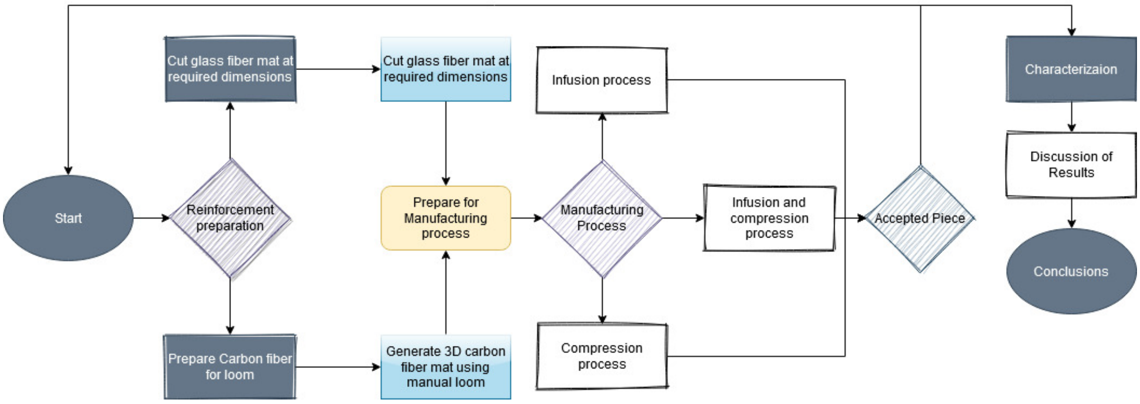


Figure 3.1: Methodology.

Epoxy resin R7000-1 was used for the first stage of this work, which consisted in finding the best manufacturing method (hand lay up, VaRTM and CM) that would give us the best mechanical properties on 2D composites. To make the comparison between the manufacturing methods (VaRTM, CM and MOD) for 3D carbon fiber composites, it was decided to equalize conditions of temperature and pressure, therefore a temperature of 45^{o}C and a pressure of 14 Ton for CM processes & -84KPa for VaRTM. For the manufacturing in these methods, the parameters (pressure and temperature) were obtained based on the literature and technical sheets of 2D and 3D composites, pressure of VaRTM process was set according to the vacuum pump used on this work. The temperature was set to 45^{o}C since the nature of the epoxy resin does not allow it to have a wide sweep as it cured at 80^{o}C. Therefore it was decided to use the average temperature of 45^{o}C. Fig. 3.2 shows a summary of the parameters and processes carried out during this work.

3.2 Materials

In the present work, 2D woven glass fibers and 3D woven carbon fiber reinforced plastics were fabricated and tested. A comparison between the different manufacturing processes and a modification is proposed.

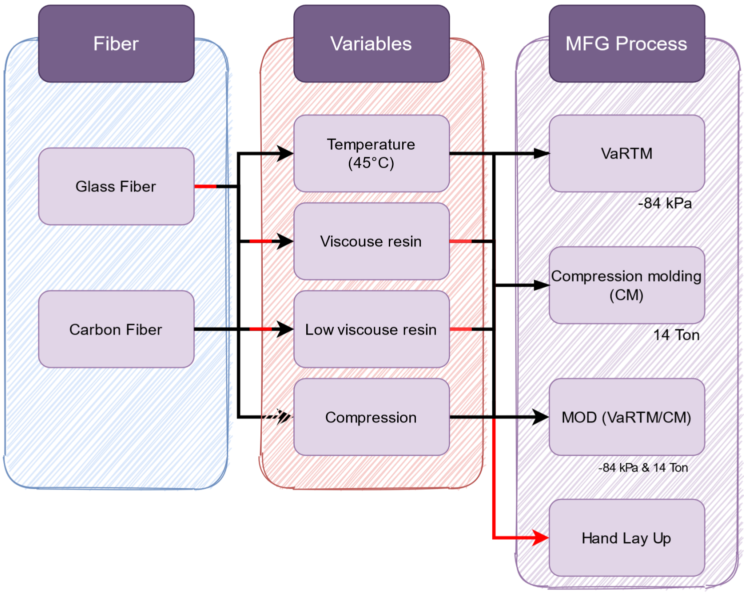


Figure 3.2: Glass and carbon fiber work done.

Ten layer of plain weaves were used as reinforcement with 90 degree ply orientation. These specimens were developed using the processes of Hand lay up, VaRTM and compression molding. Tensile specimens of glass fiber were developed by 10 plies, while f20 plies developed flexion specimens. 3D Carbon fiber weaves were developed by 21 weft plies and 1 warp ply. Table 3.1 shows all plies configuration and orientation used on this work. Carbon fiber and glass fiber reinforcements were provided by the industry.

Table 3.1: Composites stacking & Architecture

Materials	Architecture	Staking sequence
Glass Fiber (T)	Plain weave	10 plies
Glass Fiber (F)	Plain weave	20 plies
Carbon fiber	ORT-PW	Warp-21 & weft-1

As matrix, two types of epoxy resin were used, the first one was the epoxy resin R7000-1, provided by Plastiformas de Mexico, an epoxy resin for general purpose with a high viscosity of 5000-9000 cPs & an specific weight of 1.15-1.17g/cm^3, As hardener was used the HD 307, second epoxy resin was the EPOLAM 2015, provided by Sika, with a density of 1.13g/cm^3, a tensile strength of 70MPa & a flexural strength of 120MPa, and a glass transition temperature of 88 ^{o}C.

3.3 2D Woven composites

Hand lay-up laminates were developed by assembled dry plies. The process consists of a stacking sequence of resin fiber to impregnate each layer in the most homogeneous way possible, a Roll is used to distribute the resin across each layer after finishing impregnating the fiber a new layer of resin fiber is used to impregnate the

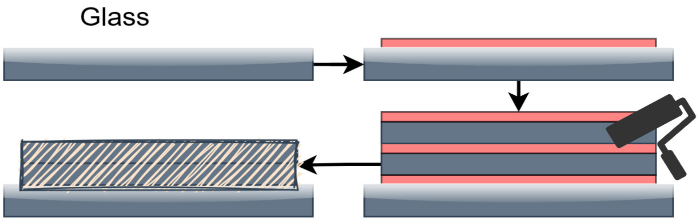


Figure 3.3: Hand lay-up process.

new added layer. This process is repeated until all plies were impregnated with resin by smoothing the surface with a roller. The process is presented in Fig. 3.3, impregnated plies were left to cure at room temperature. The same process was used on GF on compression molding process, once the fiber were fully impregnated they were compacted at 14 Ton and left to cure for 24h.

The Infusion process followed in this work is shown in Figure 3.4. The method consists of a closed mold system at which vacuum is applied. The generated suction allows the resin to flow across the system, impregnating the fibers on the process. The process ends by closing the entrance and exit valves, allowing the material to cure under vacuum. The entrance valve is located on the hose connected to the resin pot, while exit valve is located on the vacuum pump. The system was submitted to a vacuum of -25 inHg or -84 kPa for 24 hours. The materials used for this work were glass as the 'mold' surface, vacuum tape to seal the mold, vacuum bag to contain the material, peel ply to prevent the materials to stick on the composite and the distribution fabric that helps the material flow through the weaving. A vacuum pump & trap, channels, valves and pot were also used as presented on diagram 3.4. A step by step explanation of the infusion process and materials used on this work are presented on Appendix C. It is essential to mention that the laminates' surface vary on the infusion process as the two faces are under different surfaces, producing different surface finishes. The bottom surface is in contact with the glass while the upper surface is in contact with the vacuum components. Infusion configuration used on this work its shown on Figure 3.4.

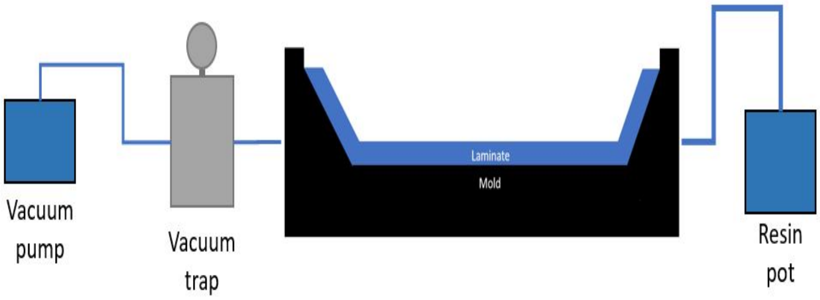


Figure 3.4: Vacuum infusion process.

3.4 3D Woven composites

For the fabrication of the fabrics a manual loom was fabricated. As regular looms the device is composed by a frame which helps to support the fibers along the device. Manual loom was developed with aluminum profiles, aluminum bases, steel shafts, and the shafts base 3.5. Aluminum bases helps to support and hold fibers to developed the x-z winding through the fabric.

(a) Manual loom design (b) Manual Loom (c) Aluminum bases

Figure 3.5: Manual Loom and design.

Manual Loom was constructed by cutting four aluminum profiles in 30 cm, and merged together using inside angles to develop the frame. Afterwards the shafts were placed into the corners as shown on Figure 3.5b. Shafts helps to place the fibers and keep the tension without tear them. Supports are then used to fix the fibers on position and create the require tension for the loom. This also helps to establish and fix the weaving dimensions that helps to improve the control quality dimensions during the manual weaving.

Figure 3.5 shows the 3D design of the manual Loom and the manual loom construction. On table 3.2 a complete list of the manual loom is presented.

Table 3.2: Manual loom components

Part name	Num. Comp.
Aluminum profiles	4
Aluminum bases	4
Steel shafts	2
Shafts base	4
Hex Nuts 36-32	4
Flat Phillips 36-32	4

Manual weaving consists on three main areas: developing of the warp yarns, adjustment of the warp yarns into the loom and weaving & cutting. As stated before on this work to develop the fiber thickness 21 plies of warp yarns were used. this help us to give the thickness and the 3D to the composite which does not consist of a simple weaving, but increase the work time considerably. Manual loom help us to achieve the tension on all 21 warp yarns while placing the wefts through the weaving. Finally the material is cut down to dimensions, eliminating the excess without affecting the weaving pattern. Examples of the final results of this process are shown on Figure 3.6.

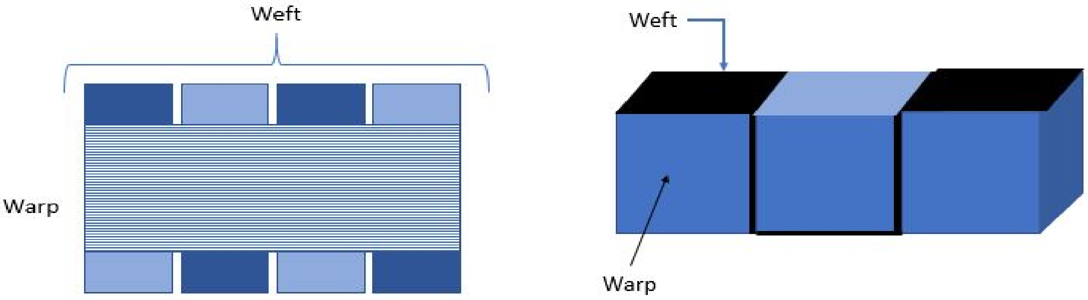
Figure 3.6: 3D carbon fiber weaving.

As the process consists on a manual elaboration of the weaving different patterns or architectures can be developed and weft and warp yarns can be modified. It is important to mention that imperfections may appeared on the weaving for being handmade. Most common problems watched during this process were: misalignment of warp or weft yarns, over tension of weft yarns that modified the number of weft yarns, width & thickness and curved warp/weft yarns if they are not stacked properly.

3D woven composites manufacturing

3D fabrics were developed using the manual loom explained on Appendix A. Manual loom consists on an aluminum square frame which helps to fix the warp yarns in position, while manually creating the cross over points with the weft yarns. Once the weft and warp yarns are in position tape is used to fix them and they are cut into dimensions of 250x135mm. Carbon fiber of 5k yarns was provided by the industry to develop the architectures. As mentioned before the matrix used for this work were the Epoxy resin R7000-1, provided by Poliformas Plasticas, and EPOLAM 2015, provided by Sika, were used. Properties of the epoxy resins used on this work can be found on Appendix B. One type of architecture was used in this work (ORT-PW) in order to understand how does the pattern behaves at different conditions. ORT plain weave was selected for its simple manufacture, which helps to minimize human error during its manufacture.

As explained before the ORT-PW consist of a plain weave which pass through all the thickness of the fabric like the plain weave pattern. On the other hand, ORT-Twill consist of a weave on each of the transversal fibers that cross along the fiber as shown. ORT-PW architecture pattern is explained by Figure 3.7 for a better understanding.



(a) 2D view (b) 3D view.

Figure 3.7: ORT PW 3D architecture pattern.

Figure 3.7a help us to understand that the 3D weaving consists on 20 warp yarns that run along the weaving, while one weft yarn was used to tie up the warp yarns and keep them in place creating the 3D weaving fabric. The 3D view 3.7b helps to clarify how does the wefts embrace the warp yarns.

3D fabrics were manufacturing developed by VaRTM, Compression molding (CM) and a proposed modification. VaRTM was developed the same way as GF specimens. The basic process can be described as the following steps: first the surface must be cleaned, then you can place the fabric & the vacuum tape, fix the peel ply, place the inlet tubes and the vacuum port, place distribution media, place the vacuum bag making sure the bag is not holed, test for air lacking and create the vacuum to impregnate the fiber. When the fiber is almost completely impregnated stop the vacuum pump and close the vacuum inlets, let the fabric under vacuum for 24h and demould. Temperature was added in this process by heating the resin to 45°C, and infusing the heated resin into the system. Main difference respect to 2D fabrics is presented on the staking as on 3D woven fabrics is only worked with 'one layer'. Pictures of the basic process are shown on Fig. 3.8

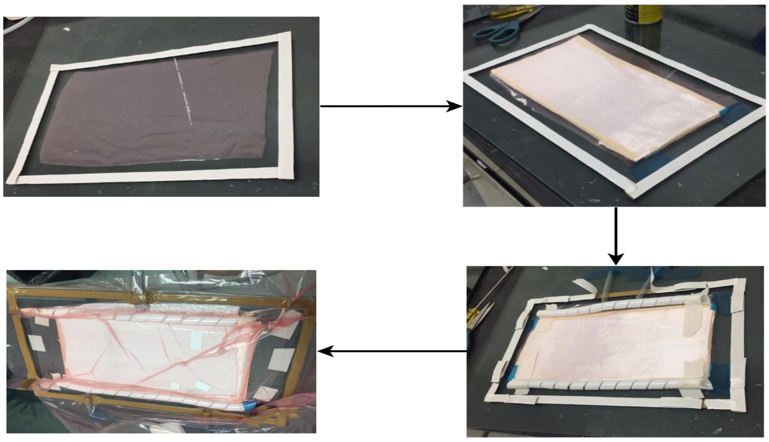


Figure 3.8: VaRTM of 3D fabrics.

CM was developed by placing a layer of resin over the mold, once the layer is the most homogeneous possible the fabric is placed over the resin taking care to not deform the yarns while placing. Finally another layer of resin is placed over the fabric and distributed along the fabric, here its also important to do it carefully to prevent deformations on the layers. Once the fabric is ready the mold is closed and compressed to 14 ton. Then, to add temperature the process both upper and bottom plates of the press were heated to 45°C for 30 min and it was then passed to a second press for 24h. Full process is described on Fig. 3.9, the green part shown on the diagram represents the mold.

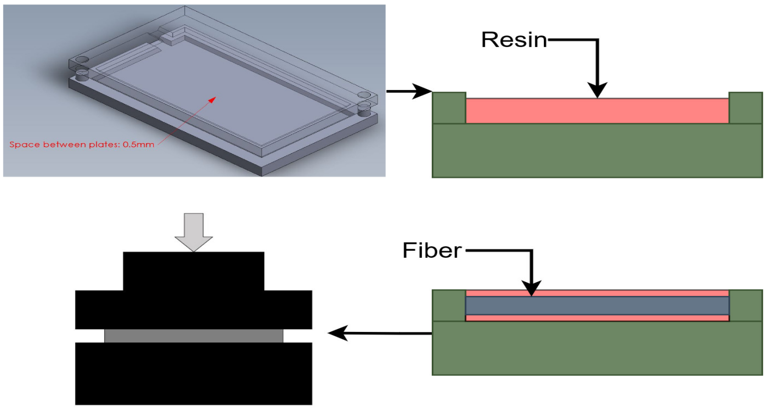


Figure 3.9: CM of 3D fabrics.

Modified manufacturing process consists on introducing the epoxy resin into the 3D fabric by VaRTM to impregnate the full fabric. Steps were developed the same way as regular VaRTM process, however once the fabric was impregnated it was left under vacuum for 25-30 min and it was demould into the CM mold. Once placed the fabric it was pressed by 14 ton for 24 hours. Temperature was added as CM process in where both plates of the press were heated at 45°C for 30 min and then it was pressed without temperature for 24h. In the case of high viscosity resins it was heated to 45°C to facilitate the vacuum process. Diagram of the process is shown on Fig. 3.10.

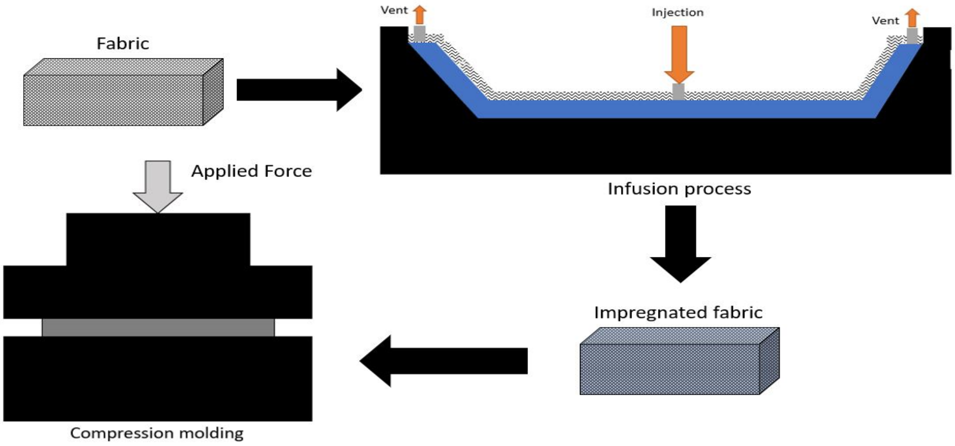


Figure 3.10: Modified process.

3.4.1 Specimen preparation

As stated before the specimens were developed by four different manufacturing process: hand lay-up, VaRTM, hand lay-up with compression molding and a modified proposal witch consist of a mixture of VaRTM with compression molding. Plain weave glass fibers were developed by hand lay-up, VaRTM & hand lay-up with compression molding, while 3D carbon fiber weaves were developed by VaRTM, hand lay-up with compression molding and the new manufacturing proposal. Table 3.3 presents the different material configurations and acronyms used on this work.

Table 3.3: Composites Specimens

Nomenclature	Manufacturing Process	Fiber	Resin
HGF7000	Hand lay-up	Glass Fiber	R7000
VGF7000	VaRTM	Glass Fiber	R7000
CGF7000	Compression molding	Glass Fiber	R7000
VGFE15	VaRTM	Glass Fiber	EPOLAM 2015
CGFE15	Compression molding	Glass Fiber	EPOLAM 2015
R7MOD	Modified Process	Carbon Fiber	R7000
R7IN	VaRTM	Carbon Fiber	R7000
R7COM	Compression molding	Carbon Fiber	R7000
EMOD	Modified Process	Carbon Fiber	EPOLAM 2015
EIN	VaRTM	Carbon Fiber	EPOLAM 2015
ECOM	Compression molding	Carbon Fiber	EPOLAM 2015

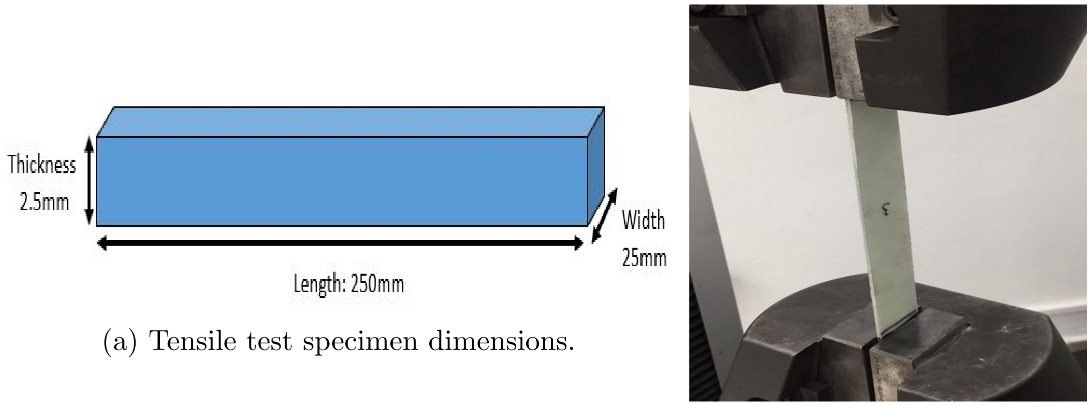
Epolam 2015 and R7000-1 epoxy resins were tested to understand how does viscosity affects on the different manufacturing process and how this affects their mechanical properties. All plates were developed with 68 to 75% of CF.

Modified manufacturing process consist on introducing the epoxy resin under the 3D composites to improve the mechanical properties. Hand lay-up process is not used on 3D composites as their thickness limits the manufacturing processes at witch this materials can be done. Basic process of the proposed modification consists on the fabric development and infusion that is then followed by a compression molding to produce the composite. As mention before compaction can help us to reduce pores and gaps among the fibers improving the composite quality & surface finish, and therefore its mechanical properties. Two molds were also used to understand how does the compaction affects the material properties. Even though both molds were developed to manufacture 250x135mm plates, the distance between plates were modified. Mold A consists of a 2.5mm space between plates while mold B were developed with a 0.5mm space between plates. Molds pictures can be found on Appendix D.

3.4.2 Characterization

Testing configuration

Tension and flexion tests were run on 2D and 3D composites, CF mold A composites were only subjected to tension tests. For all the mechanical tests (tensile and flexion stress tests) a universal testing machine from the Shimadzu, model AG-X, brand was used.



(a) Tensile test specimen dimensions.

(b) Tensile test.

Figure 3.11: (a) Sample dimensions, and (b) Sample submitted to Tensile test.

Tensile properties

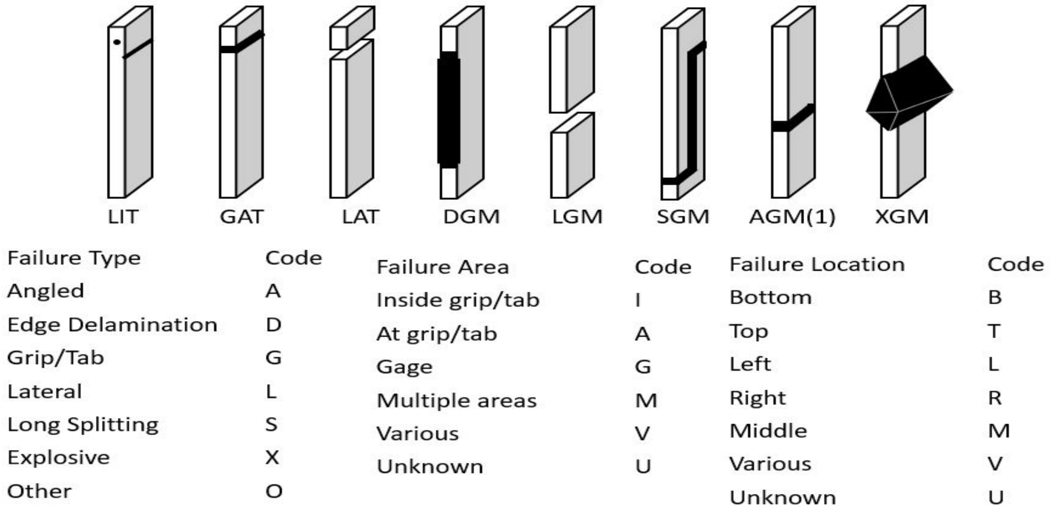
The mechanical properties of the specimens calculated in this work were the ultimate tensile strength, the tensile strain and the Young modulus. All values were determined by using the ASTM D3039 standard to determine the tensile properties of a polymer matrix. Five specimens with rectangular cross-section were cut from each of the four cases explained before. GF and CF mold A specimens dimensions are specified on Figure 3.11a., while carbon fiber mold B specimens have the same length and width than GF specimens, the thickness was varied due to manufacturing processes, a thickness of 1.3mm was used for CM and MOD manufacturing processes while a thickness of 2mm was used for VaRTM. The strips are mounted in the grips of the testing machine using a 1 mm/min rate as shown in Figure 3.11b., which records the load and deformation of the specimen. The ultimate strength of the specimen is determined by the maximum load carried in failure. The stress-strain responses are recorded to determine the Young modulus for each specimen.

All tensile test specimens were developed with tabs to ensure a failure inside the specimen area, also known as the gauge area. Tabs were also used to avoid glide on the grip area.

Mode of failure is reported according to the ASTM D3039 standard. Modes of failure are presented on Figure 3.12.

Flexural test

The mechanical properties of the flexural strength of a polymer matrix composite are determined by the ASTM D7264 standard. The specimens are supported as a beam and deflected at a constant rate of 2.45 millimeters per minute. The point load is applied at the midpoint from the supporting end. Therefore the specimen deflection at the mid portion and applied force is measured and recorded until failure occurs on either of the two surfaces. The SHIMADZU AG-X is employed to realize the test as specified before. GF specimens dimensions and test are shown on Fig 3.13. Carbon fiber mold B specimens have the same length and width than GF



Failure Type	Code
Angled	A
Edge Delamination	D
Grip/Tab	G
Lateral	L
Long Splitting	S
Explosive	X
Other	O

Failure Area	Code
Inside grip/tab	I
At grip/tab	A
Gage	G
Multiple areas	M
Various	V
Unknown	U

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

Figure 3.12: Modes of failure

specimens, the thickness was varied due to manufacturing processes, support span ratio of 1:40 was used with a thickness of 1.3mm for CM and MOD manufacturing processes while a thickness of 2mm was used for VaRTM.

Stress at the outer surface at mid span were evaluated from the shear test according to the following relation:

$$\sigma = 3\mathrm{PL} \;/\; 2\mathrm{bd}^2 \tag{3.1}$$

where P is the load at a given point on the load-deflection curve, L is the support span, b is the specimens width and d is the specimen thickness.

Strain were evaluated according to:

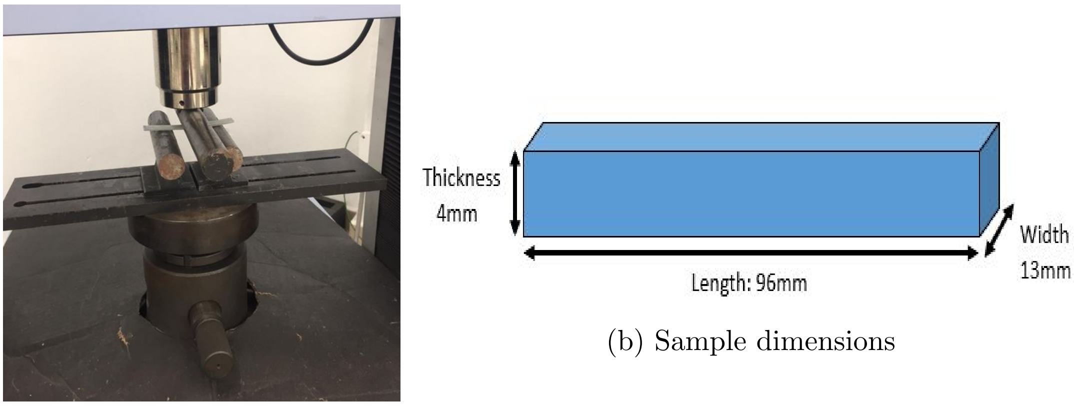
$$\epsilon = 6\xi\mathrm{h} \;/\; \mathrm{L}^2 \tag{3.2}$$

Optical microscopy

For the microstructural observations, an Olympus PMG 3 with a 10, 50x and 100x magnification was used. Microscopy analysis was developed on both glass fiber and carbon fiber specimens. And the different manufacturing processes to understand how does the different manufacturing affects the voids and rich resin areas within the specimens.

3.5 Results

Tensile and felxural results of 2D GF and 3D CF composites are presented on this section.



(a) Flexion test

(b) Sample dimensions

Figure 3.13: (*a*) Sample submitted to Flexion test, (*b*) Sample dimensions.

Tensile properties

Hand lay-up, VaRTM, compression molding and modified tensile results obtained for the tensile test given by the standard ASTM D3039 for glass and carbon fiber. Stress was calculated according to:

$$\sigma = \mathrm{P}/\ \mathrm{bd} \tag{3.3}$$

where P is the load, b is the specimens width and d is the specimen thickness. The max strain and stress recorded values of the glass fiber specimens developed by hand lay up, VaRTM and compression molding for expoxy resin R7000 and EPOLAM 2015 are shown in Table 3.4.

The stress-strain responses and the mode of failure of each specimen is reported according to the ASTM D3039 standards. Results shown that all the Hand lay-up specimens fail at the top location near the grip with an average maximum stress of 85.432 MPa.

CF mold A & B results are shown on Table 3.5. Main difference between mold A and B is the distance between plates which can be seen on Appendix D. The use of letter T represents the application of temperature during the manufacturing process, this vary according to the process as explained before.

Flexural properties

GF composites developed with R7000 and EPOLAM peoxy resin by VaRTM results are shown on Table 3.6. Max felxural stress and strain CFRP results are shown on Table 3.7 Most specimens behave on the same manner, but a clear variation is shown on the results.

where ϵ is the maximum strain at the outer surface, ξ is the mid-span deflection, L is the support span, and h is the thickness of beam.

Table 3.4: Maximum stress-strain values on tensile test of GFRP specimens

Specimen	Max stress (MPA)	Strain (%)	Mode of failure
HGF7000-P1	84.57	1.42	GAT
HGF7000-P2	89.704	1.5	SGM
HGF7000-P3	78.442	1.47	GAT
HGF7000-P4	83.874	1.62	GAT
HGF7000-P5	90.574	1.96	GAT
HGF7000-Average	85.432 ± 4.91	1.594 ± 0.217	-
VGF7000-P1	495.24	5.36	SGM
VGF7000-P2	488.15	6.10	SGM
VGF7000-P3	569.03	5.27	SGM
VGF7000-P4	410.52	6.35	SGM
VGF700000-Average	490.73 ± 64.7844	5.70 ± 0.53	-
CGF7000-P1	392.85	3.47	SGM
CGF7000-P2	398.29	3.34	SGM
CGF7000-P3	422.06	3.52	GAT
CGF7000-P4	439.39	3.59	SGM
CGF7000-P5	458.54	3.63	DGM
CGF7000-Average	422.23 ± 27.61	3.51 ± 0.11	-
VGFE15-P1	484.25	3.86	XGM
VGFE15-P2	549.81	3.16	XGM
VGFE15-P3	529.54	3.17	XGM
VGFE15-P4	497.94	3.14	XGM
VGFE15-Average	515.38 ± 29.77	3.33 ± 0.35	-
CGFE15-P1	416.25	5.25	SGM
CGFE15-P2	413.19	4.95	SGM
CGFE15-P3	301.03	5.25	SGM
CGFE15-Average	376.55 ± 66.28	5.15 ± 0.17	-

Table 3.5: Maximum stress-strain values on tensile test of CFRP specimens

Specimen	Max stress (MPA)	Strain (%)	Mode of failure
Mold A	-	-	-
ECOM-P1	658.33	5.26	DGM
ECOM-P2	588.91	4.32	DGM
ECOM-P3	583.67	4.71	SGM
ECOM-Average	610.30 ± 41.67	5.26	-
EMOD-P1	513.54	4.08	DGM
EMOD-P2	493.66	4.17	DGM
EMOD-P3	549.13	4.52	DGM
EMOD-Average	510.98 ± 28.10	4.22	-
Mold B	-	-	-
R7IN$_T$-P1	764.87	4.33	DGR
R7IN$_T$-P2	608.81	3.74	DGM
R7IN$_T$-P3	669.78	4.14	DGR
R7IN$_T$-P4	752.28	4.39	DGL
R7IN$_T$-P5	592.58	4.23	DGU
R7IN$_T$-Average	628.03 ± 79.39	4.39	-
R7COM-P1	1274.3	3.81	DGU
R7COM-P2	866.05	2.79	DGM
R7COM-P3	1129.2	2.79	SGM
R7COM-Average	974.33 ± 206.95	3.81	-
R7COM$_T$-P1	1129.1	3.73	DGM
R7COM$_T$-P2	1166.3	3.66	DGM
R7COM$_T$-P3	1206.8	3.65	SGM
R7COM$_T$-P4	1086.7	3.78	DGM
R7COM$_T$-Average	1137.4 ± 51.33	3.7	-
R7MOD$_T$-P1	1365.9	4.98	DGM
R7MOD$_T$-P2	1546.4	4.99	DGM
R7MOD$_T$-P3	1474.2	4.99	DGM
R7MOD$_T$-Average	1460.7 ± 90.84	4.99	-
EIN-P1	752.24	4.38	DGM
EIN-P2	723.31	5.25	DGM
EIN-P3	748.99	5.25	DGM
EIN-Average	690.5 ± 15.84	5.25	-
EIN$_T$-P1	651.76	3.76	DGM
EIN$_T$-P2	559.99	4.05	DGB
EIN$_T$-Average	592.85 ± 64.89	4.05	-
ECOM-P1	1167.1	3.97	DGM
ECOM-P2	1441.6	4.34	SGM
ECOM-P3	1208.9	4.51	DGR
ECOM-P4	1208.9	4.82	DGR
ECOM-P5	1039.4	3.56	DGL
ECOM-Average	1181.2 ± 145.37	4.82	-
ECOM$_T$-P1	1031.8	4.57	DGM
ECOM$_T$-P2	1147.8	4.14	DGM
ECOM$_T$-P3	1242.4	4.14	SGM
ECOM$_T$-P4	1014.7	4.83	DGM
ECOM$_T$-Average	1077 ± 106.69	4.83	-
EMOD-P1	1096.7	4.15	SGM
EMOD-P2	1195.8	4.03	SGM
EMOD-P3	1276	4.42	SGM
EMOD-Average	1146.6 ± 89.81	4.42	-
EMOD$_T$-P1	1168.7	4.07	DGM
EMOD$_T$-P2	1546.4	5	SGM
EMOD$_T$-P3	1474.2	4.99	DGM
EMOD$_T$-Average	1208.1 ± 200.49	4.99	-

Table 3.6: Maximum stress-strain values on flexion test of GFRP specimens developed by hand lay-up

Specimen	Max stress (MPA)	Strain (%)
P1	272.357	6.78
P2	435.876	6.39
P3	517.039	6.69
P4	531.123	6.43
P5	413.441	6.08
P6	502.422	6.35
P7	471.252	5.41
P8	533.264	6.8
P9	412.411	7.11
P10	446.764	5.91
Average	453.59 ± 78.59	6.39 ± 0.496

Table 3.7: Maximum stress-strain values on flexion test of CFRP specimens

Specimen	Max stress (MPA)	Strain (%)
R7COM-P1	1553.0	14.01
R7COM-P2	1008.9	9.43
R7COM-P3	1044.5	13.47
R7COM-Average	1007.0 ± 304.38	14.01
R7COM$_T$-P1	2041.7	15.06
R7COM$_T$-P2	1431.5	12.7
R7COM$_T$-P3	1350.4	10.89
R7COM$_T$-Average	1316.4 ± 377.89	15.06
R7MOD$_T$-P1	1311.3	13.13
R7MOD$_T$-P2	1141.0	10.94
R7MOD$_T$-P3	1345.7	12.07
R7MOD$_T$-P4	1365.3	13.04
R7MOD$_T$-Average	1365.3 ± 102.3	13.04
EIN-P1	172.3	19.25
EIN-P2	139.93	10.21
EIN-P3	157.86	15.07
EIN-Average	133.25 ± 16.21	19.25
EIN$_T$-P1	457.47	13.23
EIN$_T$-P2	434.85	12.79
EIN$_T$-Average	443.45 ± 15.99	12.92
ECOM-P1	1512.5	13.07
ECOM-P2	1599.0	12.17
ECOM-Average	1520.4 ± 61.16	13.07
EMOD-P1	834.75	10.44
EMOD-P2	1087.5	9.63
EMOD-Average	920.19 ± 178.72	10.04
EMOD$_T$-P1	1159.0	16.94
EMOD$_T$-P2	873.91	12.91
EMOD$_T$-P3	829.98	12.47
EMOD$_T$-Average	840.5 ± 178.63	16.94

Chapter 4

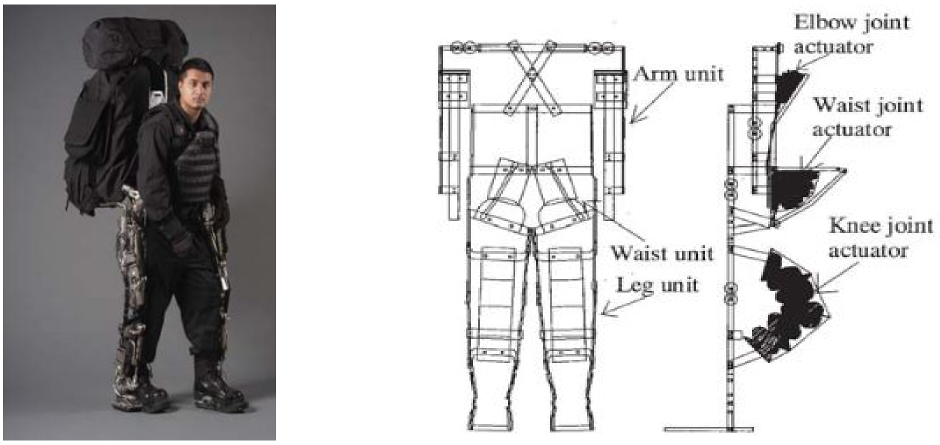
Exoskeleton Component Design

4.1 Introduction

Exoskeletons have been defined in different ways as a general concept we can conclude that exoskeletons are wearable devices that work in parallel with their users in order to increase physical performance to complete certain tasks. Exoskeletons are widely used in various engineering application tasks such as assisting patients with walking disorders and enhance the endurance and strength of operators in the industry. However, exoskeletons are limited by the state of the current technology and human imagination. Meaning that exoskeletons could be used on a wide number of areas in any physical activity of a person [47, 122].

Exoskeletons can be classified according to their design characteristics that may vary from their structure (soft or rigid), action (active or passive), power source and purpose (rehabilitation or performance assist) [47].

Exoskeletons started date back to the 19th century, several devices as the "apparatus for facilitating walking, running, and jumping" and "apparatus to facilitate walking and running" [123, 124]. Appeared with unique designs that consist of springs and links to redistribute the energy given by the user while moving [123]. Exoskeletons programs keep expanding and by 1965 Hardiman I Exoskeleton was developed with 30 degree of freedoms and a weight of 680 Kgs [122].



(a) (b)

Figure 4.1: (a) BLEEX [125], and (b) Nurse-Assisting Exoskeleton [126].

The Berkeley load-carrying human Exoskeleton (BLEEX) was developed in 2004, this exoskeleton provides its wearer augmented strength and endurance while keeping a walking speed of 0.9 m/s with a payload up to 75Kg. Other exoskeletons as (Human Universal Load-Carrier Exoskeleton) HULC and (Human Universal Mobility Assistance) HUMA were also developed for human power augmentation. With the help of high-pressure hydraulic actuators, HULC can help to carry payloads up to 91Kg while walking with minimal fatigue. While HUMA exoskeleton can provide assistance to carry heavy backpack load while assisting human locomotion at a walking speed of 1.39 m/s [122]. Figure 4.1 shows BLEEX and a Nurse assisting exoskeletons.

This study aimed to understand how does 3D woven composites could be used to develop a lower-body link exoskeleton. Different materials that can be used and have been used for the exoskeletons have been discussed. Based on the research done the two most appropriate materials and the manufactured of 3D woven composites have been chosen for the exoskeleton link frame. A finite element analysis has been performed on the selected materials a volume and weight comparison was developed to choose the most appropriate material.

4.1.1 Mechanical design

An important aspect that a well-designed exoskeleton has is the capacity to transfer the user's weight to the ground, making the user free from the gravity effect [127]. Another important roles for the design of exoskeletons are:

- Comfortable and ergonomic design.
- High maneuverability.
- Lightweight and strong structure.
- Adaptability to different users.
- User safety.

Concerns as restore function, storability, cleaning, ease to wear are reported in [44]. Other concerns presented of exoskeleton users could be found and should be considered during the exoskeleton design.

4.1.2 Material performance

Material forms a crucial aspect on exoskeleton design. Light and strong materials are required to develop the exoskeleton frame, this is due to several aspects as lower energy consumption, less power requirement and ability to support torque & the users body weight [128].

A crucial parameter for design is the strength to weight ratio of the material also known as the specific strength. Which represents the strength of the material divided by its density. The specific strength is given by:

$$SS = \sigma \; / \; \rho \tag{4.1}$$

Where, σ is the tensile strength, and ρ is the material density.

Stiffness of the material is also important to understand if the component is the strong enough to withstand the load without bend or buckle. The index for maximizing stiffness is given by:

$$K = E^{0.5} \; / \; \rho \tag{4.2}$$

Where, E is the young modulus, and ρ is the material density. Other important parameters that have a relevant impact on the application and selection of the material component are the manufacture, volume, weight and cost.

4.1.3 Material analysis

The most commonly used materials for the frame of exoskeletons due to their good mechanical properties (stiffness and strength) are metal alloys like 316L & 304 stainless steel, titanium, and aluminum alloys. Some composites that have been used on exoskeletons are fiberglass, Kevlar, and carbon fiber. This is due to their high strength to density ratio [129, 127]. Table 4.1 presents the tensile strength, young modules, and density as well as the specific strength and stiffness.

Table 4.1: Material properties used for exoskeleton frame [92, 105, 129, 128].

Material	ρ (Kg/m^3)	σ (MPa)	E (GPa)	SS	K
304 Stainless steel	7850	510	190	0.065	0.00176
316L Stainless steel	7850	480	190	0.061	0.00175
Aluminum 7075	2810	503	71.7	0.179	0.00301
Ti-6AL-7Nb	4510	995	100	0.221	0.00222
2D Carbon fiber	1456	359.56	44.2	0.247	0.0046
Fiberglass (SMC)	1710	240	17	0.1404	0.0024
3D woven CF (MOD$_T$)	1730.4	1460.7	32.37	0.8441	0.0033

From Table 4.1 we can conclude that stainless steel although having good mechanical properties that could be used for the development of exoskeletons frames, other materials as aluminum (AL7068) and titanium with better properties could be used. The main problem with materials as aluminum AL7068, and Mg alloys (AZ91D) and titanium (Ti-6AL-7Nb) is their availability and price [129]. Between the composite materials, the developed 3D ORT woven composites present the better mechanical properties in the relationship of specific strength, while keeping a high stiffness. 2D carbon fiber presents the lower density material, but presents a lack of specific strength compared to 3D woven composites. However, the material presents the highest stiffness.

After analyzing the mechanical properties, price, availability and resistance of each material presented before, the materials selected were the aluminum AL7075, 2D carbon fiber and 3D woven carbon fiber.

4.1.4 Finite Element Analysis.

As a complex structure several forces act on different parts of the knee joint as well as torque generated by the load transfer. Forces vary across the time according to the person position, activity (walking), etc. The data used to understand the loads that the component needs to bear were obtained from [130]. On this work we are going to focus on the data collected from the 101Kg person walking at 4Km/h. For the finite element analysis, it was assumed that all forces action on the knee joint were transferred to the exoskeleton. On this particular case only the forces were considered on the study. Table 4.2 shows the detail results of the study.

Table 4.2: Forces and acting moments on different massed people [130].

Mass (Kg)	F_x (N)	F_y (N)	F_z (N)	M_x (N)	M_y (N)	M_z (N)
91	44.63	-2026.4	-223.18	-1250	-4200	-40700
96	-282.5	-2392.1	-433.2	-3110	-8660	-21000
101	-128.8	-2338.3	-69.4	-2970	-7130	-28100

The data from Solid-works AL7075-T7451 was used to develop the finite element analysis for aluminum. FEA for the composites was developed by the data obtained from experimentation and by the data obtained from the micro-mechanical analysis of Chamis developed with the information provided by the suppliers. Figure 4.2 shows the equations used on the micro-mechanical model of Chamis. Abbreviations and data of the model are presented on Appendix D.

$$E_y = \frac{E_m}{1-\sqrt{V_f}*(1-\frac{E_m}{E_{Tf}})}$$

$$E_z = E_y$$

$$G_{xy} = \frac{G_m}{1-\sqrt{V_f}*(1-\frac{G_m}{G_{Tf}})}$$

$$G_{xz} = G_{xy}$$

$$G_{yz} = \frac{G_m}{1-\sqrt{V_f}*(1-\frac{G_m}{G_{TTf}})}$$

$$v_{xy} = v_{LTf}*V_f + v_m(1-V_f)$$

$$v_{xz} = v_{xy}$$

$$X_t = V_f * X_{tf}$$

$$Y_t = X_{tm}*(1-(\sqrt{V_f}-V_f)(1-\frac{E_m}{E_{Tf}}))$$

$$X_c = V_f * X_{cf}$$

$$Y_c = X_{cm}*(1-(\sqrt{V_f}-V_f)(1-\frac{E_m}{E_{Tf}}))$$

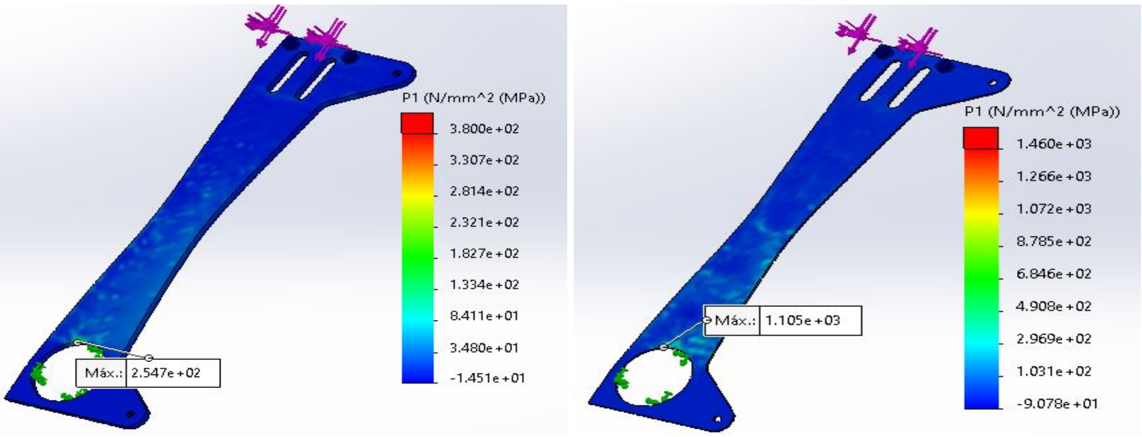
$$S_{xy} = S_m*(1-(\sqrt{V_f}-V_f)(1-\frac{G_m}{G_{LTf}}))$$

$$v_{xz} \rightarrow \textit{In transversely isotropic material it is fulfilled: } G_{yz} = \frac{E_m}{2(1+v_{yz})}$$

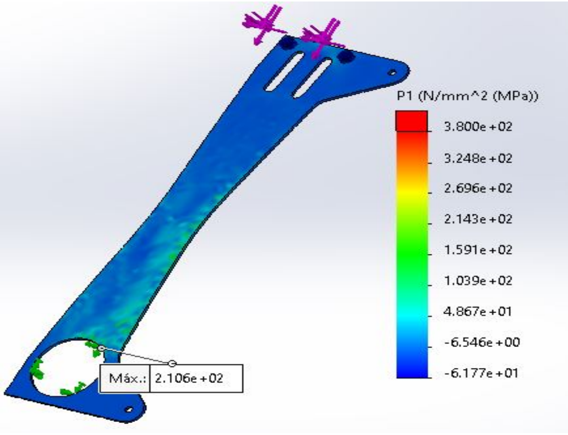
Figure 4.2: Chamis micro-mechanical model.

Figure 4.3 shows the FEA results from aluminum, 2D woven CF, and 3D woven carbon fiber.

Safety factor for all pieces were kept at 1.3+-0.05. Max stress reported by the 3D Woven CF (3DWCF) is around 1.105x10^3 MPa while 2D woven carbon fiber works



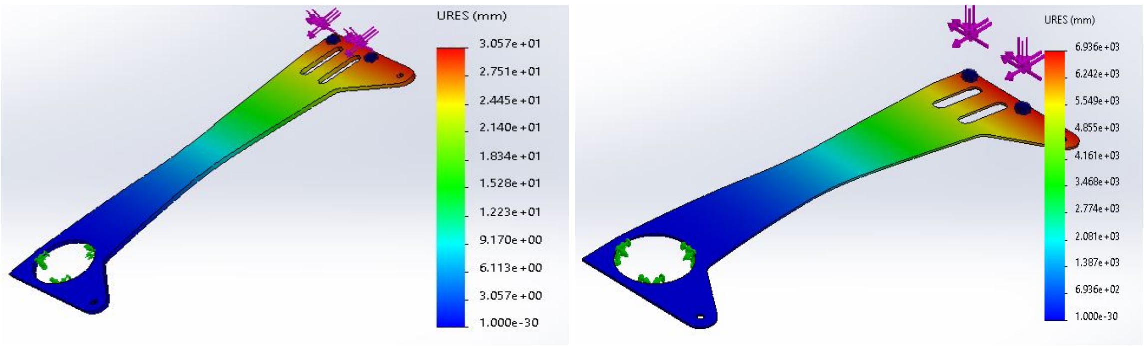
(a) 2D woven Carbon fiber (b) 3D woven carbon fiber



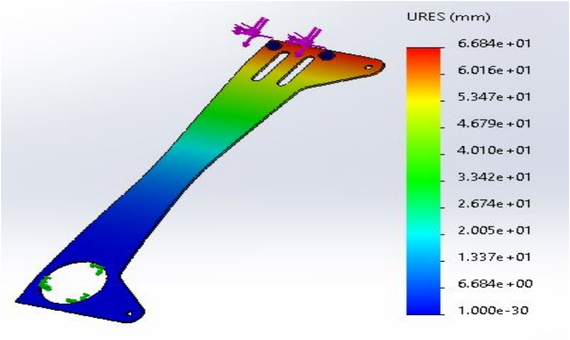
(c) AL7075

Figure 4.3: RTM process: (*a*) 2D woven Carbon fiber, (*b*) 3D woven carbon fiber, and (*c*) AL7075.

around 2.547x10^2 MPa and AL7075 worked around 2.106x10^2 MPa. It is important to mention that 3DWCF component suffers a thickness reduction due to outstanding properties, from 2 to 1.35mm this changed helps to minimize the component volume and weight. The volume of Al7075 and 2D woven CF stayed at 30930.58mm^3 and 69284.50mm^3 respectively, while 3DWCF was reduced to 20878.14mm^3. 3DWCF presented the lower mass at 36.34g while AL7075 and 2D woven CF presented 87.53 and 98.66g respectively. Figure 4.4 shows the displacements of each material. Without the structure 3DWCF presents the maximum displacement this can be expected due to their thickness reduction, however, a displacement on aluminum and 2D woven CF are also found. It should be considered that with the addition of the full exoskeleton displacements should be considerably reduced.



(a) 2D woven Carbon fiber (b) 3D woven carbon fiber



(c) AL7075

Figure 4.4: RTM process: (a) 2D woven Carbon fiber, (b) 3D woven carbon fiber, and (c) AL7075.

Chapter 5

Results and Discussion

5.1 Fabrics development & manufacturing

3D woven fabrics manual fabrication consists on developing twenty warp yarns per 1 weft yarn as described in Fig. 3.7. Tension was used to place the warp yarns on position to finally pass the weft yarns as required. Tension is needed to keep yarn into place, although tension on weft yarns needs to be limited to prevent deformation on weft yarns as shown in Fig. 5.1. Red lines show how deformation occur on the weft yarns causing the main effects on the fabrics: an oval effect given by a contraction in the crossover points and a parable effect developed by a shifting level caused by the excess weft.

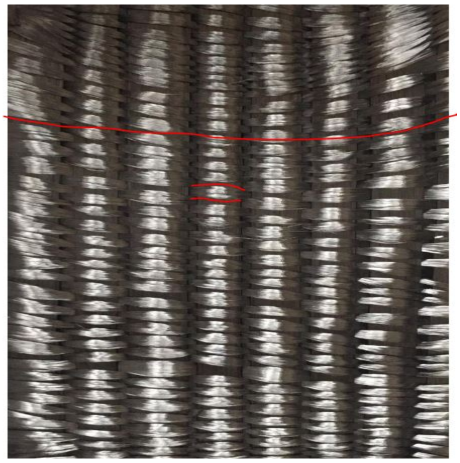


Figure 5.1: Over tension of weft yarns

Hand lay up has proven low mechanical properties compared to VaRTM and compression molding as expected. This could be due to the low time compaction and the lack of "global" compaction that is generated during the manufacturing by the roll. VaRTM and compression molding, on the other hand, presented good mechanical properties with good quality finished. Clear differences can be seen on both processes while compression molding could be used with viscous and low viscous resins, VaRTM is only recommended to being used on low viscous resin as the process is significantly alternated by the resin flow through the composite, which can cause an insufficient impregnation through the composite or even an unfinished product. Parameters as cured and gel time are also essential to take into account while developing VaRTM. Compression molding specimens keep constant finish across the specimen, however, VaRTM species appeared to have a better finish on the glass face.

3D woven fabric specimens present more differences in the finishes than 2D woven composites, this could be due to being a single piece rather than a stacking sequence. VaRTM 3D woven fabrics present a clear difference in their finishes. An undulation can be seen on the bag finish while the glass finish presents a smooth part, as presented in Fig. 5.2. Other defects that could be produced on 3D woven fabrics are insufficient impregnation if the infusion is not developed correctly and demolding problems due to the lack of release agent.

Figure 5.2: 3D woven composites VaRTM defects.

Mold A specimens presented several manufacturing defects as poor impregnation, gaps on the crossovers, and poor resin distribution, as shown on Fig. 5.3. All this defects could be explained due to the lack of compression on the specimens.

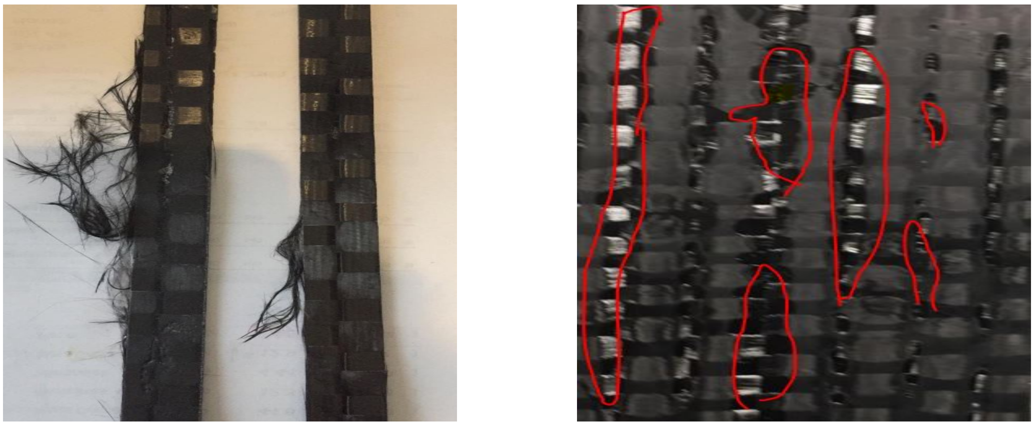


Figure 5.3: 3D woven composites Mold A defects.

Mold B specimens have proven better finishes across the material while reducing manufacturing problems presented on mold A as poor impregnation, gaps on the crossovers and resin distribution.

Thermogravimetric Analysis (TGA) was developed to understand the thermal stability of the material, and understand at which point a degradation of temperature could be observed. Taking the TGA analysis presented in Fig. 5.4, the fact that the processing temperature of the epoxy resins is up to 80°C, and a modification of gel and curing time a middle temperature of 45°C was used to help the viscous and non-viscous resin to flow and improve the resin distribution across the system.

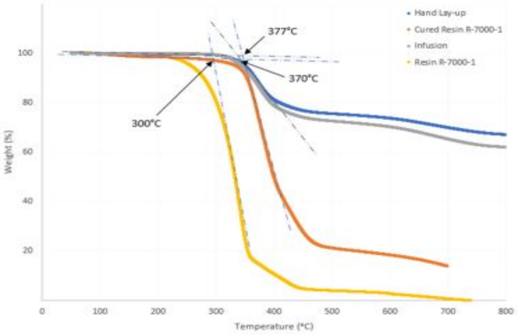
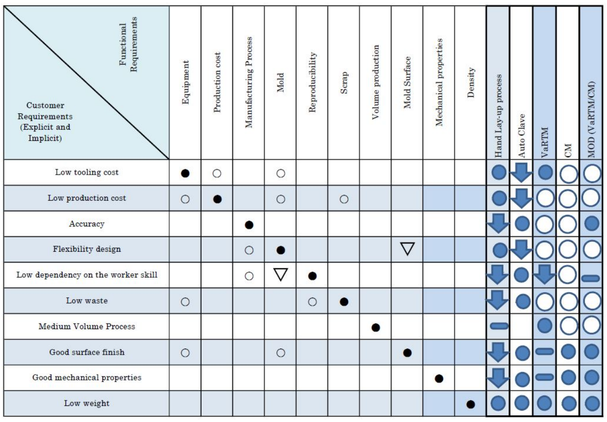


Figure 5.4: Thermogravimetric analysis

Figure 5.5 presents a comparison between different manufacturing processes for composites with the proposed methods (MOD). The modified process presented the better properties used with high viscous resins, this process helps to improve the resin distribution across the fabric while taking advantage of the compaction developed by CM molding. It is recommended to use this method for 3D woven composites for low to medium volume production, as production of exoskeletons. Components dimensions are limited by the mold capabilities and the process is also dependent on the worker's skills. Despite this, the new process presents better repeatability and precision with respect to CM and Infusion.

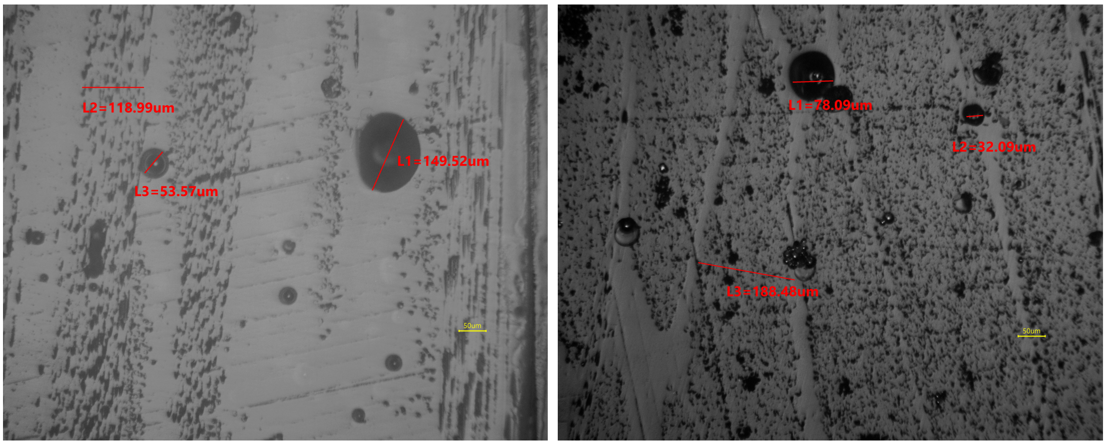


Functional Requirements Customer Requirements (Explicit and Implicit)	Equipment	Production cost	Manufacturing Process	Mold	Reproducibility	Scrap	Volume production	Mold Surface	Mechanical properties	Density	Hand Lay-up process	Auto Clave	VaRTM	CM	MOD (VaRTM/CM)
Low tooling cost	●	○		○							●	⬇	●	○	○
Low production cost	○	●		○		○					●	⬇	○	○	○
Accuracy			●								⬇	●	○	○	●
Flexibility design			○	●				▽			●	⬇	○	○	○
Low dependency on the worker skill			○	▽	●						⬇	●	⬇	○	▬
Low waste	○				○	●					⬇	●	○	○	○
Medium Volume Process							●				▬		●	○	○
Good surface finish	○			○				●			⬇	●	▬	●	●
Good mechanical properties									●		⬇	●	▬	●	●
Low weight										●	●	●	●	●	●

Figure 5.5: Manufacturing processes comparison.

5.2 Microstructural studies

White phase represents the matrix materials while the gray/black parts represents the fiber. Voids can be differentiated as black spots. Fig. 5.6 shows optical cross sections of both GF laminates made by hand lay-up and GF laminates made by VaRTM. Voids on both cases appeared to concentrate outside the fiber layers within the RRA. RRA is more visible on the specimens developed by hand lay-up process than the specimens developed by VaRTM. It can be related to the fact that in the VaRTM process the fibers are more compact together minimizing the RRA across the composite. Voids could look also significantly longer on hand lay up process this could also be related to the lack of compaction during the process.



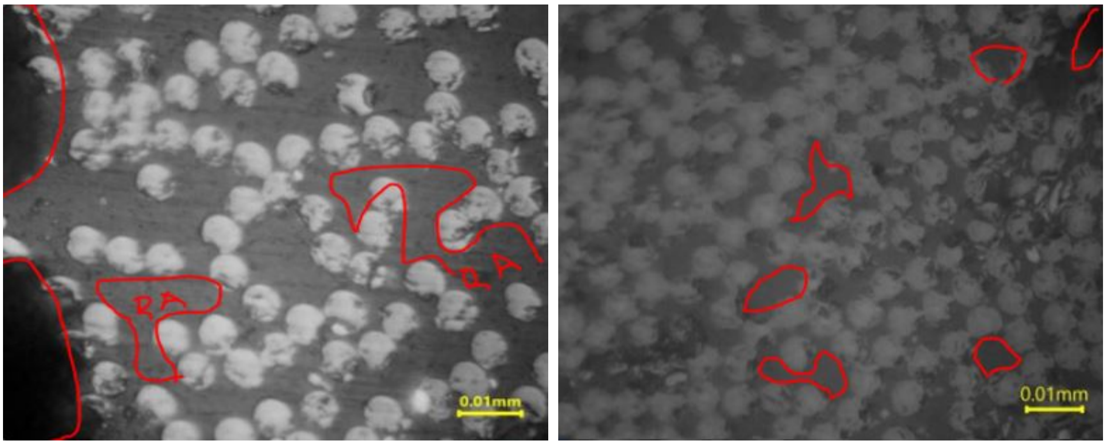
(a) (b)

Figure 5.6: Optical cross section of (a) hand lay-up, and (b) VaRTM comparing the voids and rich resin areas (RRA).

Fig. 5.7 shows optical cross sections of CF laminates developed by CM using two mold variations, mold A & mold B, explained in Appendix D. Voids appeared to be higher on Mold A than Mold B. This could be due to the lack of compaction as mold A has a greater thickness between plates compared to mold B. RRA are found on both process, however RRA is higher on mold A than mold B, this could also be related to the lack of compaction during the process. It can be concluded that RRA and voids can be decreased by enhancing the compaction during the CM process.

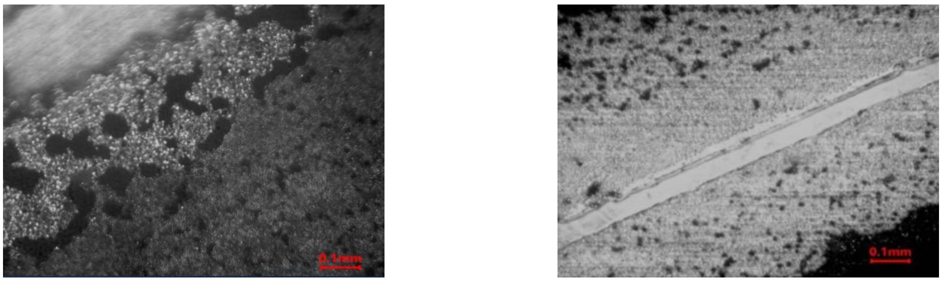
Fig. 5.8 shows the optical cross sections of CF laminates developed by CM process using high and low viscosity resins micrographs confirm that void and RRA could still be found on both process, however a greater concentration of voids could be found on high viscosity resins this could be due to the lack of distribution as the high viscosity of the resin does not allow it to flow as much as the low viscosity resin. RRA can be found near the weft yarn, as seen like the line that goes across (b). It can be concluded that voids can be related to the resin distribution that is affected by the resin viscosity and that the weft cross over can create RRA with could work as stress concentration points.

Fig. 5.9 shows the optical cross section of CM specimens developed with & without temperature, VaRTM specimens developed with & without temperature. As shown on figures (a) and (b) temperature helps to control void content on CM specimens although RRA can still be found with almost the same amount. While on VaRTM process voids seems to be low in comparison with CM, RRA are still found on higher content than the CM process. It can be concluded from (c) and (d) that



(a) (b)

Figure 5.7: Optical cross section of CM developed by (a) mold A, and (b) mold B comparing the voids and rich resin areas (RRA).



(a) (b)

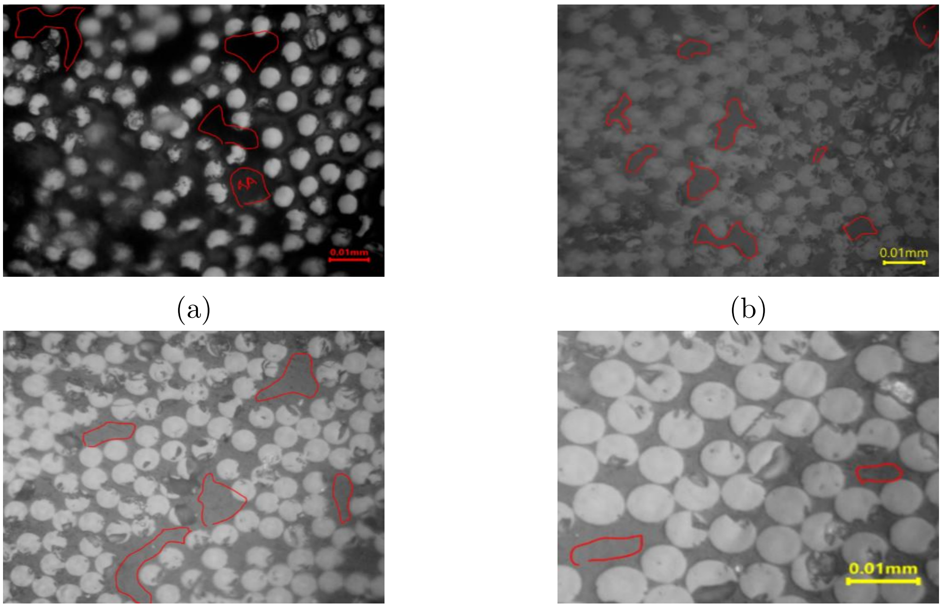
Figure 5.8: Optical cross section of CM developed with (a) high viscosity resin, and (b) low viscosity resin comparing the voids and rich resin areas (RRA).

temperature helps to reduce RRA on VaRTM process although the improvement is almost neglectable.

5.3 Tension experimental analysis

The results obtained for the conducted tensile test as per the ASTM D3039 standard are given in Tables 3.4 & 3.5.

Strain stress graphs of GFRP of each specimen of Hand lay-up, VaRTM & CM are shown in Fig. 5.10, as presented on the graphs all specimens behave in a similar way, however, CM glass fiber specimens presents better repeatability than Hand lay-up and VaRTM. As shown on microscopy process with lower RRA and voids, CM & VaRTM, presents better mechanical properties than specimens developed with high RRA and voids as hand lay-up. This could be for the low compression presented during the process as the resin is distribute across the fabrics with a roller, also its important to mention that the applied force developed with the roller is only presented during the impregnation unlike CM & VaRTM in witch the compaction is developed during all the process.



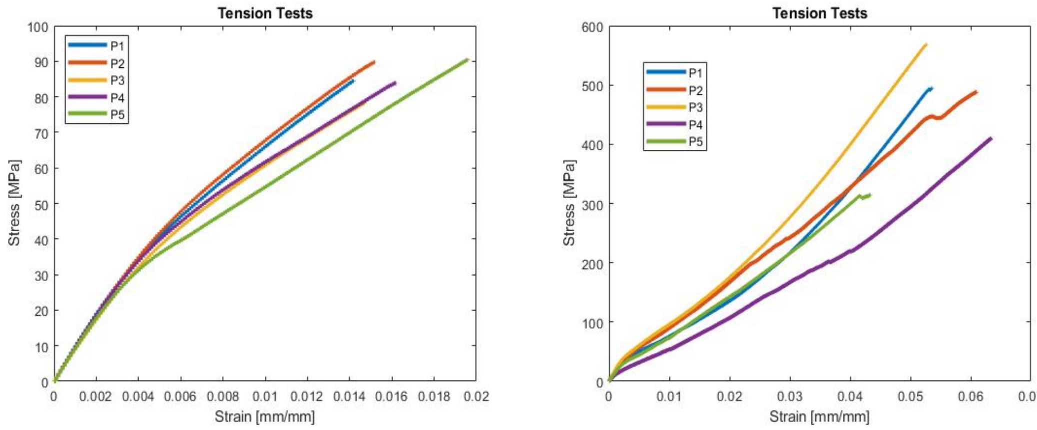
(a) (b) (c) (d)

Figure 5.9: Optical cross section of (a) CM developed without temperature, and (b) CM developed with temperature, (c) VaRTM developed without temperature, and (d) VaRTM developed with temperature, resin comparing the voids and rich resin areas (RRA).

The stress-strain graph representing the maximum recorded values concerning the three different manufacturing methods of GF are shown in Fig. 5.11. Where C is the CM process, I is the VaRTM process, and H is the hand lay-up process. The obtained stress-strain graph indicates that the hand lay up method shows lower stress capabilities and a brittle behavior while VaRTM & compression Molding show better results comparing to hand lay up. On the other hand VaRTM demonstrated more ductile capabilities than compression molding specimens. Maximum tensile strength of the resin EPOLAM 2015 has shown an increment of 5% and a decrement of 10.8 % on VaRTM and compression molding process compared to the epoxy resin R700 specimens, respectively.

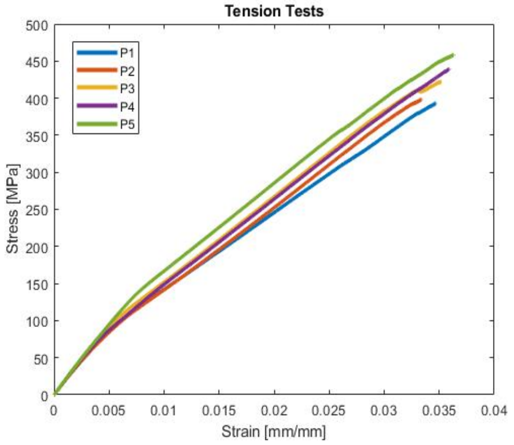
It can be concluded from GF experiments that the compaction plays a significant role on the in-plane mechanical properties of the specimens, as shown with the low mechanical properties presented by the hand lay up process which is almost three times lower than CM and VaRTM process, as shown on Fig. 5.11. As expected 2D woven fabrics developed by VaRTM present better mechanical properties while working with low viscosity resins than hand lay up processes, however an improvement on mechanical properties can be seen on hand lay up process compared with high viscosity resins this could be due to low viscosity helping to distribute better across the plates improving the interfacial bounding of the material.

Figure 5.12 a comparison with the results reported by [131] was developed between the different manufacturing processes of 2D woven glass fiber composites to have a clearer representation of the obtained results. In the comparison we can appreciate an increment on the 2D woven composites developed on this work reporting an increment of 82 and 84 percent for VaRTM and CM respectively. Hand lay up



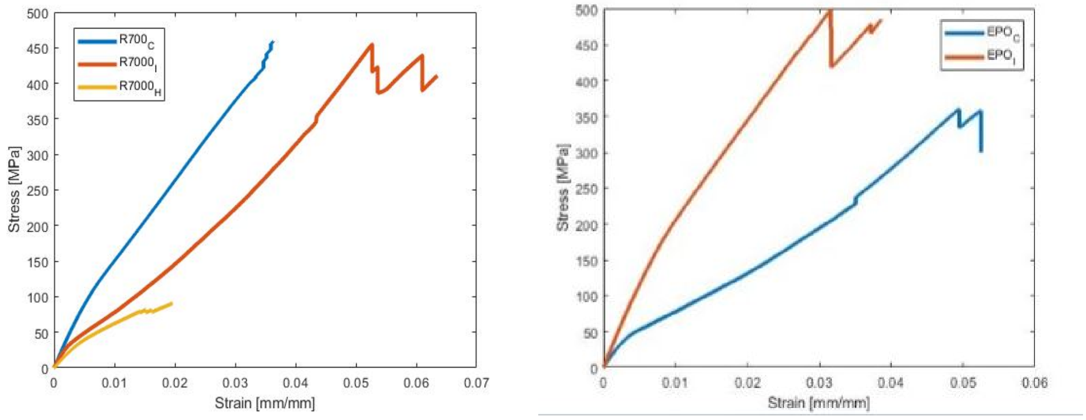
(a) Hand lay-up.

(b) VaRTM.



(c) Compression molding.

Figure 5.10: Strain-stress diagram of GF/R7000 tensile tests



(a)

(b)

Figure 5.11: Strain-stress diagram of GF specimens developed by (a) high viscosity resin, (b) low viscosity resin

presented the lowest mechanical properties.

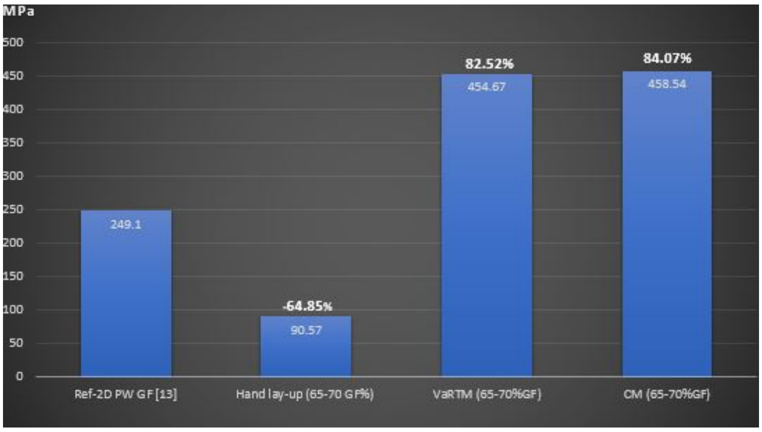


Figure 5.12: Comparison of tension properties of glass fiber composites.

Fig. 5.13 shows the quantitative effects of the stress-strain graph comparison of mold A and mold B. As implied by the experiment, only the CM process were evaluated. Where COM represents CM as described before, MOD is the modification proposed on this work, A & B representing mold A and B respectively. It can be concluded from the figure that compaction takes a principal role on the mechanical properties of the specimens as both process, CM and MOD, on mold B presents an increment of 105.4 and 124.3 percent of improvement compared to mold A specimens.

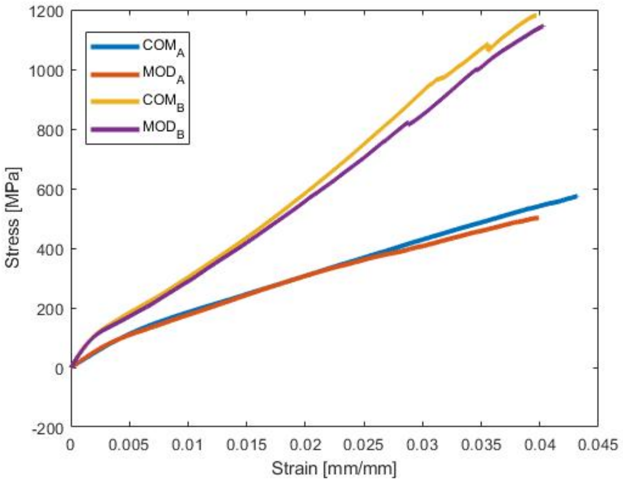


Figure 5.13: Comparison of tension properties of Mold A and Mold B.

Fig. 5.14 shows the effects of high viscosity resin on the different manufacturing processes. High viscous resins are limited on infusion process as their viscosity does not allow them to flow across the fabrics, developing poor impregnation processes that are why on most of these cases temperature was used in order to work with this material. CM processes were all developed with mold B as it shows better properties than mold A. Temperature is represented as T. Same acronyms were used for COM and MOD process, although VaRTM was added to represent VaRTM process. It can be concluded that CM processes present better mechanical properties on comparison to VaRTM process, however MOD process presents the better behavior on high viscous resin matrix composites this is due to the combination of infusion and CM on the specimen.

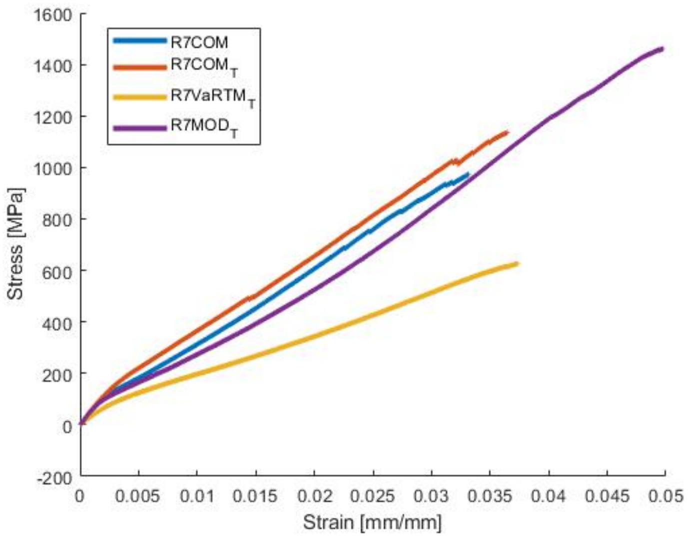


Figure 5.14: Comparison of high viscous resin CF composites.

Fig. 5.15 shows the effects of low viscosity resin on the different manufacturing processes. The same acronyms were used for COM, MOD and VaRTM process, as for temperature (T). it can be concluded that CM processes present better mechanical properties than VaRTM process. An increment of 66.13 and 61.18 percent on CM and MOD can be found respect to VaRTM without temperature and an increment of 68.07 and 69.91 percent on CM and MOD respectively be found with temperature.

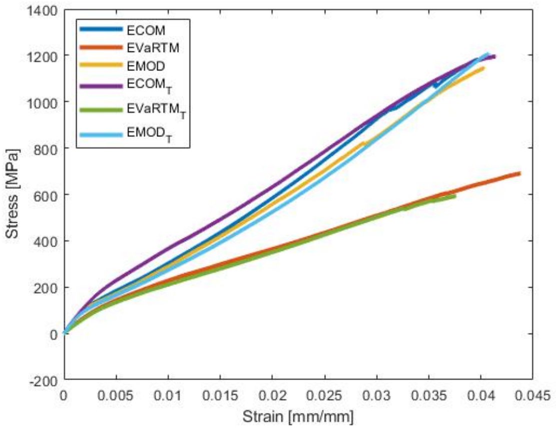
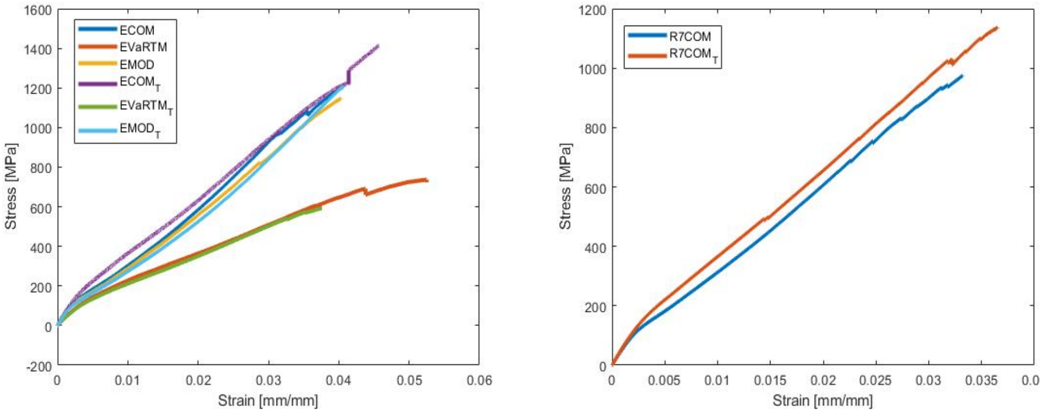


Figure 5.15: Comparison of low viscous resin CF composites.

Fig. 5.16 shows the effects of temperature on low and high viscosity resin on the different manufacturing processes. The same acronyms were used for COM, MOD and VaRTM process, as for temperature (T). From the graphs it can be concluded that CM and MOD process presents and increases the in-plane mechanical properties on low vicuous resin matrix while using temperature, however the MOD process is relatively low (5.36 %) on comparison with CM process (26.15 %). VaRTM process did not present an increase in the mechanical properties this could be due to manufacturing errors. The temperature on CM of high viscous resin composites presents an increment of 16.73 %. It can be generally concluded that temperature has a positive effect on CM processes this is due to the improvement of viscosity and distribution across the fabric, enhancing the interfacial bonding on the composite.



(a) (b)

Figure 5.16: Strain-stress diagram of CF specimens developed by (a) low viscosity resin, (b) high viscosity resin temperature comparison

Fig. 5.17 shows a comparison of 3D woven ORT composites made by [132] and aluminum 7075 with the different manufacturing processes developed by a high viscous resin (R7000-1). MOD process presents the better mechanical properties used with high viscous resins which reported an increment of 246% & 105% compared to aluminum and [132]. Compression molding processes shown the better mechanical properties.

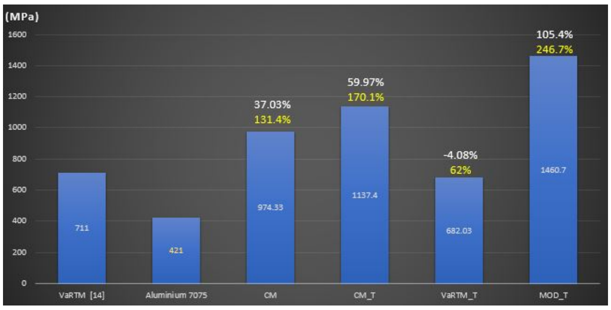


Figure 5.17: Comparison of high viscous resin processes with 3D ORT composites and aluminum 7075.

Fig. 5.18 shows a comparison of 3D woven ORT composites made by [132] and aluminum 7075 with the different manufacturing processes developed by a low viscous resin (EPOLAM-2015). From this we can conclude that CM process presents the better mechanical properties. We can appreciate an increment of 180% on traditional CM without temperature, and 183% with temperature compared to the aluminum 7075, MOD process reported significant improvements respect to the aluminum with increments of 172% and 186% with and without temperature respectively.

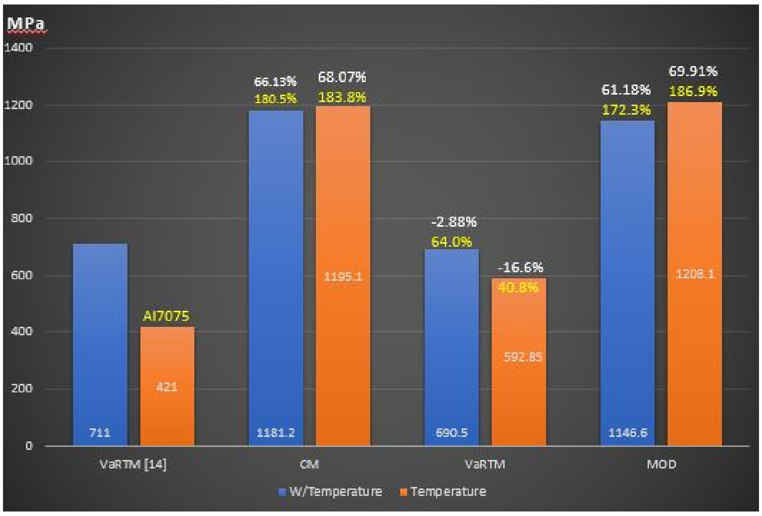


Figure 5.18: Comparison of low viscous resin processes with 3D ORT composites and aluminum 7075.

5.4 Flexural experimental analysis

Outside properties as mentioned before are important to understand in order to know how does the material behaves to outside of plane loads that are more realistic than in plane loads. The results obtained for conducted flexion test as per the ASTM D7264 standard are given in Table 3.6 & 3.7 for GF and CF respectively.

Fig. 5.19 shows the effect of high viscosity resin on the different manufacturing processes. The same acronyms were used for COM and MOD processes, as for temperature (T). It can be concluded that CM and MOD present similar flexion properties, while CM process presents a more ductile behavior. MOD process also presents better properties when used with high viscous resin as in tension tests.

Fig. 5.20 shows the effect of low viscosity resin on the different manufacturing processes. The same acronyms were used for COM, MOD and VaRTM process, as for temperature (T). It can be concluded that CM presents better performance using low viscous resin.

Fig. 5.21 shows the effects of temperature on low and high viscosity resin on the different manufacturing processes. The same acronyms were used for COM, MOD and VaRTM process, as for temperature (T). From the graphs, it can be concluded that low viscous resin flexural properties can be enhanced on VaRTM process using temperature, however MOD process does not present significant changes in its properties. On the other hand CM of high viscous resin presents an increment of 30.71 % using temperature compared to without temperature.

Fig. 5.22 shows a comparison of the different developed manufacturing processes. High viscous resin process shows an increment on the materials properties when temperature is used on CM processes. While traditional CM presents the better

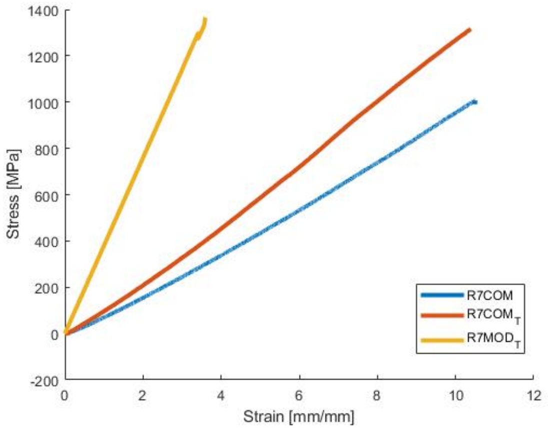


Figure 5.19: Comparison of high viscous resin CF composites.

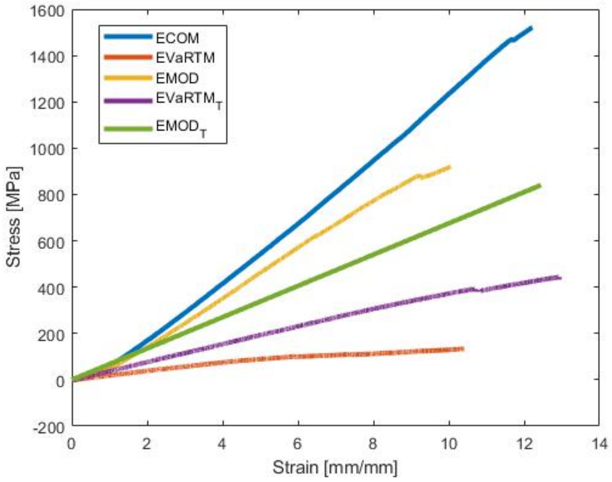
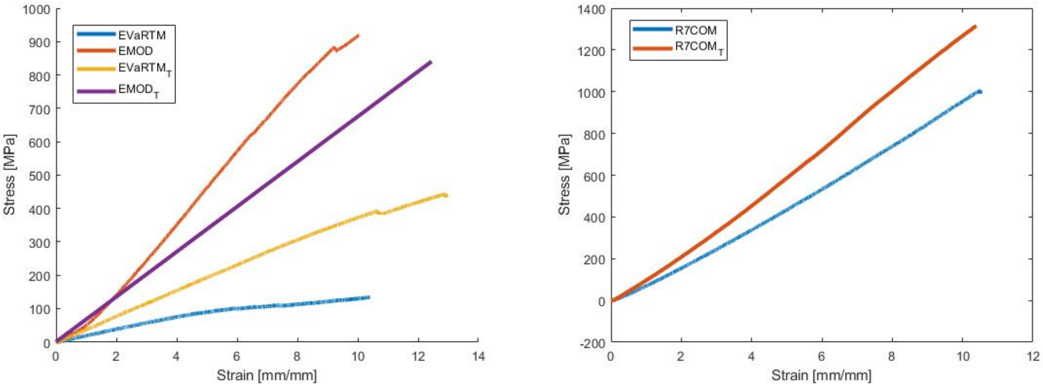


Figure 5.20: Comparison of low viscous resin CF composites.

mechanical properties when a low viscous resin is used, this is due to the generation of voids within the MOD process when a low viscous resin is used.

5.5 Finite Element Analysis.

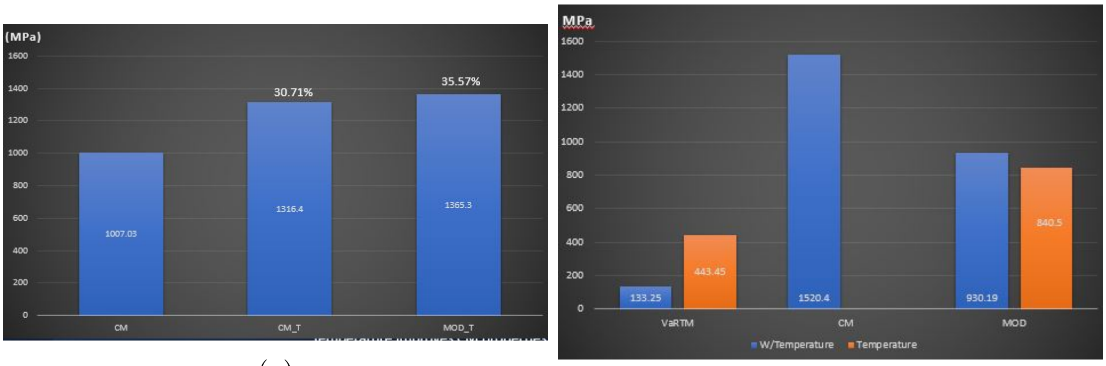
From the Finite element analysis shown in Fig. 5.23 we can conclude that a weight reduction of 58 percent could be achieved using 3D woven composites. And it proves to be the best material for exoskeletons composites with a weight reduction of 58% and 61% compared to aluminum and 2D woven composites, respectively. 3D woven composites also presented the lowest volume due to the thickness reduction (1.35mm).



(a)

(b)

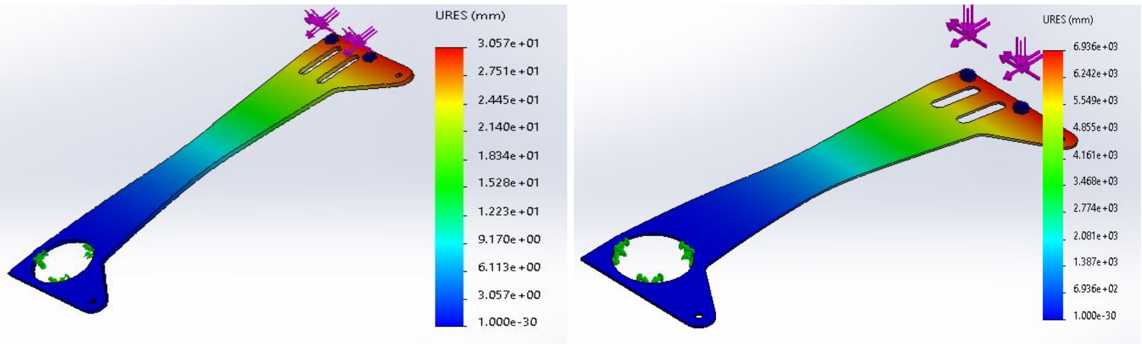
Figure 5.21: Strain-stress diagram of CF specimens developed by (a) low viscosity resin, (b) high viscosity resin temperature comparison



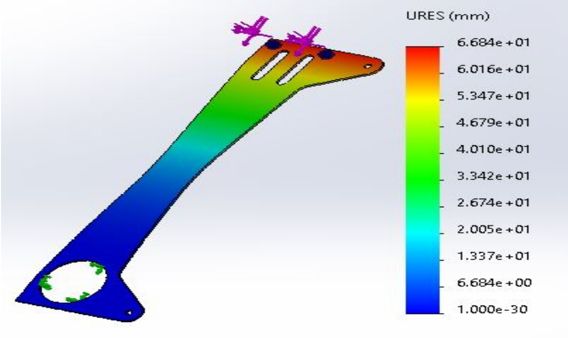
(a)

(b)

Figure 5.22: Flexure properties reported by different manufacturing processes developed by (a) high viscosity resin, and (b) Low viscosity resin.



(a) 2D woven Carbon fiber (b) 3D woven carbon fiber



(c) AL7075

Figure 5.23: RTM process: (*a*) 2D woven Carbon fiber, (*b*) 3D woven carbon fiber, and (*c*) AL7075.

Conclusions

Conclusions

Based on the experimental results, the following points can be concluded:

- Mechanical properties of 3D woven composites were improved by using compression molding to ensure a better resin distribution and impregnation through the composite.
- 3D woven composites developed by CM achieved lighter and slimmer components for exoskeletons compared to commercial materials like aluminum 7075. A reduction of 58 percent was reported using 3D woven composites instead of aluminum 7075.
- CM is a suitable technology to produce 3D laminate composites with enhanced mechanical properties. A better distribution of the resin is achieved using the CM process, improving the materials' in-plane and out-of-plane mechanical properties.
- Mechanical properties of 3D woven composites are affected by the applied compaction of the material. Lack of compaction during CM leads to insufficient impregnation across the composite. Diminishing the mechanical properties of the materials. As shown in the results when the compaction is increased with mold B the tensile properties of the material double the reported by the low compaction composites (Mold A).
- Finishes are affected considerably by the manufacturing process of 3D laminates. Glass finish on 3D woven composites helps to keep an even flat finished on the materials. 3D woven composites developed by VaRTM present a good finished on the glass part, but undulations could be appreciated on the bag finished.
- Mechanical tests have proven that temperature during the manufacturing process can improve the mechanical properties of the materials, this is due to the improvement of impregnation and adhesion between the resin and the fibers.
- Better results are achieved on MOD process using high viscous resins this could be due to an enhancing in the distribution of the matrix across the fiber.
- The proposed method presents details in the volume of production of the piece, in addition to being dependent on the skill of the worker. Despite this, the new process presents better repeatability and precision with respect to CM and

Infusion. In addition to presenting the best tensile mechanical properties when used with high viscosity resins. Process is also limited to a low to medium volume production.

- High viscous produce defects as rich resin areas on the infusion manufacturing process that act as stress concentrators leading to early failure.
- Hand lay Up has proven lower mechanical properties compared to CM and VaRTM on 2D woven laminates. This is due to the lack of compaction compared to CM and VaRTM processes.
- Parameters as cure & gel time should be considered during the infusion process. This parameters affect the impregnation of the composite, and the resin distribution on the material. Affecting the overall properties of the material.
- Over tension on Weft yarn may cause deformation on the fabrics. An oval effect is developed by stacking and tension the weft yarns creating deformations (misalignment) and affecting the fibers capabilities to withstand the applied loads to the material.

Contributions

The following contributions were developed during this work:

- Study the effects of variables as viscosity, temperature, manufacturing process and compaction on 3D woven composites.
- Elaboration of 3D woven composites with superior mechanical properties due to CM, despite being low used for this materials as reported in the literature.
- Procedure to fabricate 3D Woven composites by CM, VaRTM and a proposed method.
- Elaboration of 3D woven composites.

Future work

This work could be continued by:

- Testing the effects of CM on complex parts for industrial scaling. Pressure vary across the mold and can affect the resin distribution across the part. Further studies about how does the resin can concentrate across the mold.
- Studying the rheological properties of the material to understand the energy absorption capabilities of the material.
- Studying the effects of CM on more architectures. Composite properties change according to the architecture used, that is why its important to understand how does CM processes can affect the architectures properties.

- Studying the effects of post curing process on 3D composites. Post curing has presented relevant changes on the mechanical properties of the materials. It is important to understand how does this post process can affect the material properties. Temperature distribution and curing across the composite can be affected by the materials architecture.
- Studying the effects of recycling on 3D woven composites. The ecological footprint pf the materials is an important aspect that must be taken into account for a better use of resources.
- Studying the campling methods of exoskeletons to carry out an integration of the component in the assembly. Combination of materials is common on the application of different products. It is crucial to integrate the components on different structures to fully display the material capabilities. And achieve high quality exoskeletons.
- Testing of mechanical cyclic properties to understand the performance of the specimens, life time and durability.

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Appendix A

Resin data sheet

A.1 Epoxy Resin R-7000-1

A.1.1 Application form

The epoxy system for structural lamination has been characterized by its low viscosity and exceptional ability to improve fiberglass reinforcement, multiple layers of reinforcement can be easily penetrated without excessive build-up of resin. The extraordinary finish produced makes this system ideal in the production of uniform laminates. Benefits:

- High reproduction.
- High solvent resistance.
- Adequate consistency for ease and handling.
- Strong and dimensionally stable finishes.

Resin characteristics:

Table A.1: Epoxy Resin R-7000-1 properties

	RE 7000-1	HD 307
Appearance	Transparent liquid free of lumps and suspended particles	Transparent liquid free of lumps and suspended particles
Color Garder Maximum	2	9
Viscosity 25C cPs	5000-9000	40-90
Specific weight 25C	1.15 to 1.17	0.98 to 1.02

A.1.2 Cured

It is recommended to let it cure for 12 hours at room temperature, then 6 hours at 65 ° C and finally 6 hours at 95 ° C.

Table A.2: Weight ratio

RE 7000-1	100 parts by weight
HD-307	15 parts by weight

Gel time at 25C - (25-35) min
Handling time - (30-40) min

Table A.3: Typical system properties

Tensile stress	144.79 Mpa
Compressive stress	128.93 Mpa
Bending stress	20 Mpa
Shore hardness D	90

A.2 EPOLAM 2015 RESIN

A.2.1 Applications

- Production of composite structures by wet lay-up methods.
- Vacuum and low pressure injection and by filament winding.
- Good behavior for wood impregnation.

A.2.2 Properties

- Low viscosity.
- Good mechanical properties.
- Good behavior in moist environment.

A.2.3 Processing

To obtain the desired temperature resistance and the optimal mechanical properties it is necessary to make a post-treatment of EPOLAM 2015 system. The thermal treatment takes place 24 to 48 hours after application according to the hardener. In order to avoid any distortion risks it is recommended to put the part on a frame before curing by plateau values.

Average values obtained on standardized specimens of pure resin / Hardening 24 hrs at 23°C + 16 hrs at 80°C.

A.2.4 Precautions and Storage

Normal health and safety precautions should be observed when handling these products:

- Ensure good ventilation.
- Wear gloves and safety glasses.

Table A.4: EPOLAM 2015 RESIN properties

		Resin EPOLAM 2015	Hardener 2014	Hardener 2015	Hardener 2016
Mixing ratio by weight		100	32	32	32
Aspect		liquid	liquid	liquid	liquid
Color		light amber	light amber	colorless	light amber
Brookfield LVT viscosity at 25 C		1300-1800	60-80	60-80	25-35
Density at 25 C	ISO 1675-85	1.13-1.17	0.94-0.98	0.93-0.97	0.96-1.00
Brookfield LVT viscosity at 25 C	-	mPas	550-750	500-600	400-500
Specific gravity at 25 C	ISO 2781-88		1.10-1.14	1.06-1.10	1.12-1.16
Pot life at 25 C		min	50-70	125-155	360-450
Gelation time at 23 C on laminate	LDT051-98	hr	2.5	6	8
Demolding time at 23 C on laminate		hr	18	24	48

Table A.5: Mechanical and thermal properties at 23^oC

			2014	2015	2016
Glass transition temperature	DSC-Mettler	^{o}C	91	88	81
Flexural modulus of elasticity	ISO 178-93	MPa	3.1	3.0	2.9
Maximal flexural strength	ISO 178-93	MPa	120	120	110
Tensile strength	ISO 527-96	MPa	70	70	73
Elongation at break	ISO 527-96	%	5	6	7
CHARPY shock resistance	SO 179/D	KJ/m2	40	55	43
Hardness	ISO 868-85	Shore D15	83	82	84

For further information, please consult the product safety data sheet. Use within 24 months of the manufacturing date. Expiry date indicated on the packaging

Appendix B

Infusion process

Infusion process can be divided in two main sections; The mold preparation and the resin infusion. Mold preparation consists on three steps. Firstly on cleaning the mold surface. Secondly, prepare the mold area by delimiting the work area, on this particular work we are working with 26x18cm laminates. Finally on adding the release agent into the mold, placing on the fibers and the rest of the vacuum components. Infusion process also consists on three main steps. First a verification of vacuum is required to secure the vacuum on the system and avoid leaks that affects the infusion process. Second the resin is prepared and degassed to remove trapped air. Finally the mold is submitted to vacuum to impregnated the material. List of materials are shown on Table B.1.

Table B.1: Infusion system components.

Competent	Specifications
Fiber	Glass fiber
Epoxy Resin	R-7000-1/HD-307
Vacuum bag	Should be bigger than laminates area
Vacuum pump	2 Stage Vacuum Pump, 1/3HP, 2.4 CFM, 110/220V
Vacuum trap	Airtech Vacuum trap
Sealant Tape	Sealant Tape
Spiral Tubing	1/2’ Spiral Tubing
Peel ply	Peel ply
Flow media	Flow media
Hoses	Infusion hoses of 1/4’ and 1/2’
Valves	1/2’ and 1/4’ valves
T fittings	1/2’ T fittings
Tape	Masking tape

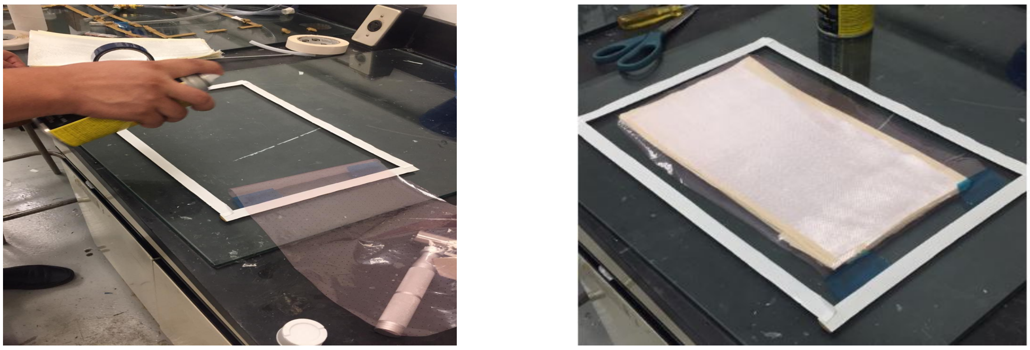
First step consist on prepare the mold surface witch is glass as shown on the Figure B.1a. Work area is cleaned with acetone. First the sealant tape is used to delimit the work zone as shown on Figure B.1b, afterwards the sealant release agent is placed on the fibers zone to prevent the fibers and resin to stick on the surface. Work area should be higher than the laminate dimensions as the vacuum bag and peel ply.

Fabrics are plied over the work area stack on the desire configuration. Release agent is used to cover the work area B.2a. In this particular case all fabrics are stack on 90 degrees, afterwards the peel ply is placed over the Fabrics as shown

(a) Cleaning the mold surface. (b) Delimitation of the work area.

Figure B.1: Mold preparation.

on Figure B.2b. As mention before peel ply should be bigger than the laminate to ensure it can cover all the laminates area, as this component help us to prevent the other components to stick on the fabric. Tape is used to ensure the peel ply keeps on position.



(a) Release agent application. (b) Fiber and peel ply positioning.

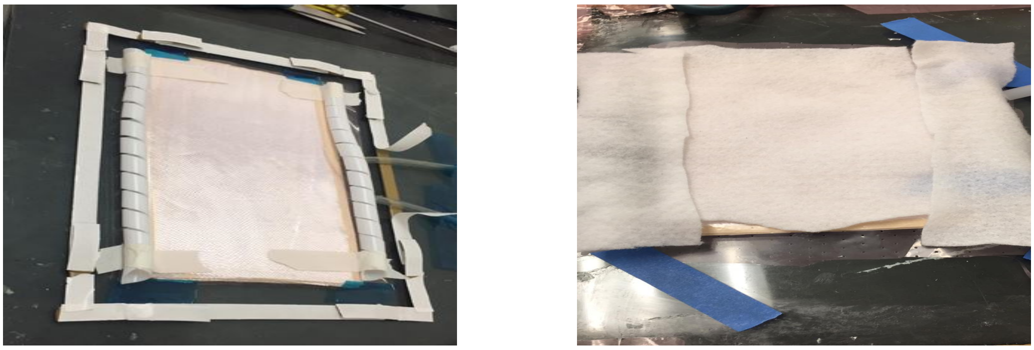
Figure B.2: Fiber and peel ply positioning.

Spiral tubing then is placed along the fibers as shown on Figure B.3a. Spiral tubing is fixed by tape also. Flow media is placed over the fibers and the Spiral tubing to help the fiber flow through the mold as shown on Figure B.3b. Flow media also help us to prevent that the spiral tubing may pierce through the vacuum bag.

Infusion inlet hoses and resin hose are placed as shown on Figure B.4a. Hoses should be placed the nearest possible to the spiral tubing, to help the rein flow. Sealant tape folds are added, as shown on figure B.4b to increase the infusion drag it also helps to prevent leaks on the system.

Finally the vacuum bag is placed over the sealant tape as shown on Figure B.5. A vacuum test is run to verified that the work area is free of leaks. This is done by vacuum the system and closing the entrance and exit valves and turn down the vacuum pump. The resin trap is then closed to separate the vacuum on different areas. A 10 min test is done by waiting to see if there is no pressure drop through the work area. This can also be done by verifying that the vacuum displayed on the pressure gauge do not fall after opening the resin trap valve.

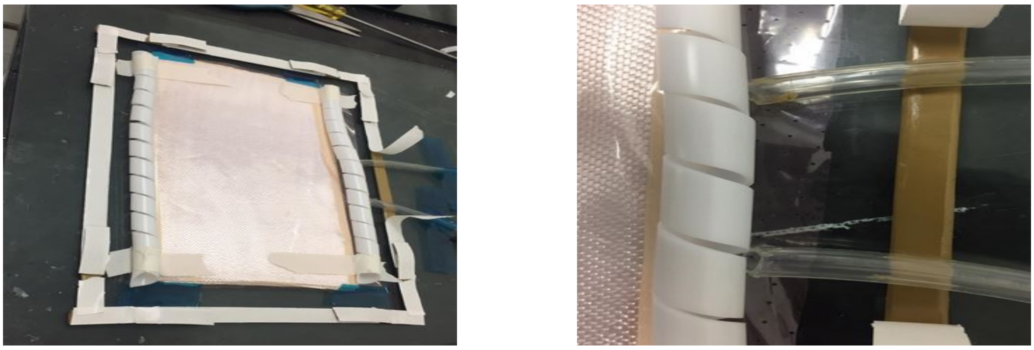
Finally the resin is prepared as described by the provider and placed on the resin pot that is connected to the resin hose. Resin valve is open allowing the resin to flow though the material as shown on Figure B.6a. When the resin arrives to entrance



(a) Tubing positioning.

(b) Flow media positioning.

Figure B.3: Flow media and tubing positioning.



(a) Hose positioning.

(b) Hose positioning near spiral.

spiral the vacuum pump is turn off and resin valve is closed, leaving the fabrics under vacuum. The material is left to cure as shown on Figure B.6b.

Figure B.5: Vacuum bag positioning.

(a) Mold prepared to infusion.

(b) Resin impregnation by RI process.

Figure B.6: Mold preparation.

Appendix C

Mold design

In this work we managed two types of molds of same dimensions. Only difference between the two molds is the plates distance during the compaction. Mold A has a distance of 2.5mm between the plates, while mold B has a distance of 0.5mm. Both molds were developed to produce plates of 250mm length and 135mm width. Figure C.1 and C.2 shown mold A and B respectively.

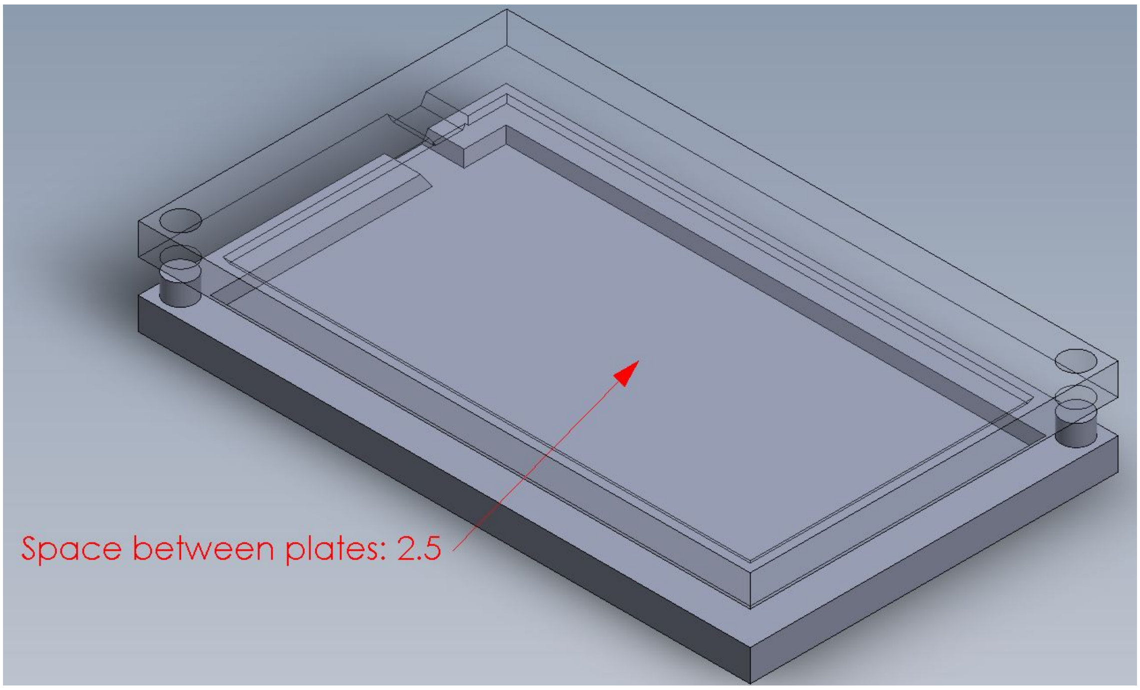


Figure C.1: Molde A.

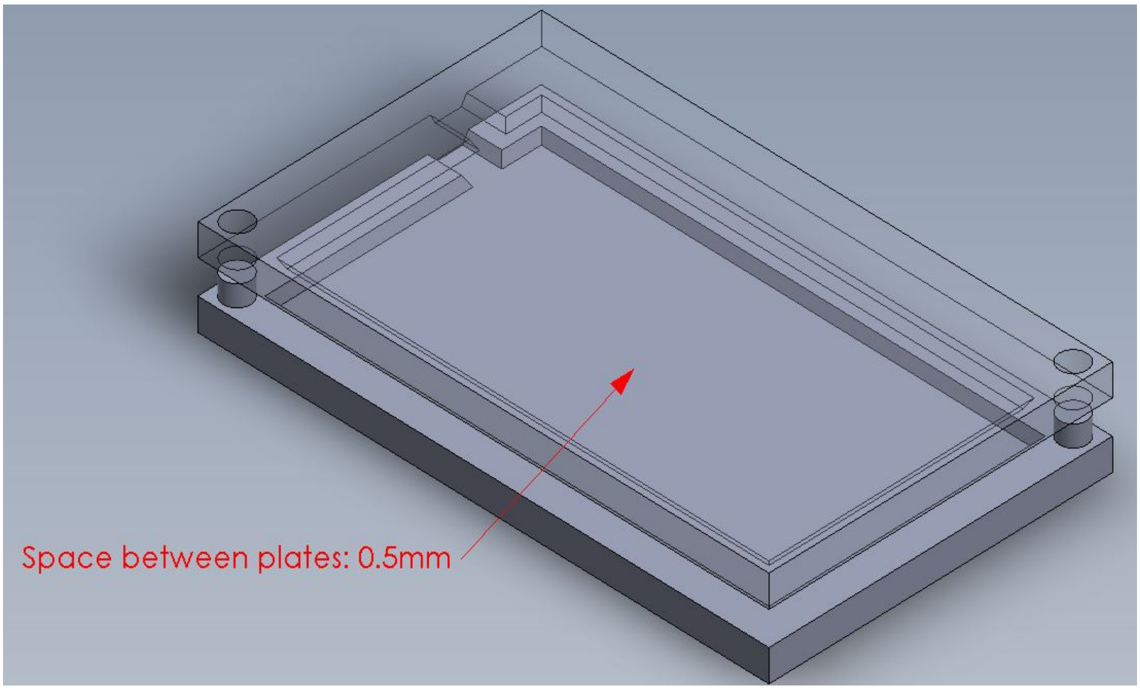
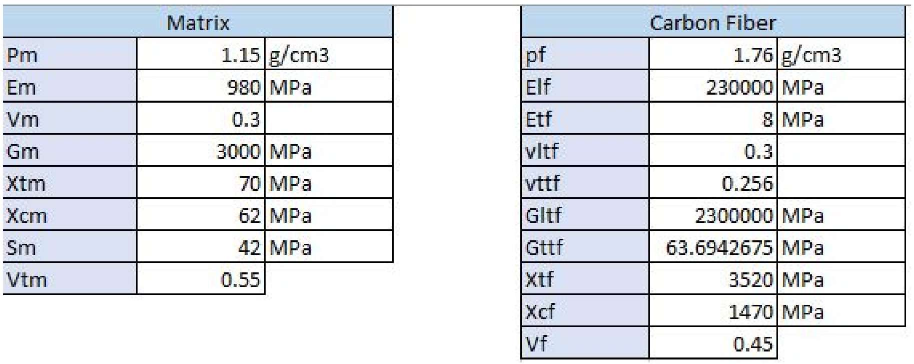


Figure C.2: Molde B.

Appendix D

Abbreviations

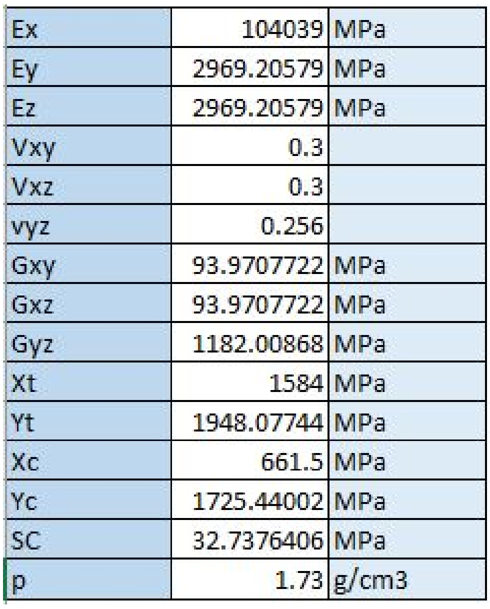
D.1 Data



Matrix		
Pm	1.15	g/cm3
Em	980	MPa
Vm	0.3	
Gm	3000	MPa
Xtm	70	MPa
Xcm	62	MPa
Sm	42	MPa
Vtm	0.55	

Carbon Fiber		
pf	1.76	g/cm3
Elf	230000	MPa
Etf	8	MPa
vltf	0.3	
vttf	0.256	
Gltf	2300000	MPa
Gttf	63.6942675	MPa
Xtf	3520	MPa
Xcf	1470	MPa
Vf	0.45	

Figure D.1: Data.



Ex	104039	MPa
Ey	2969.20579	MPa
Ez	2969.20579	MPa
Vxy	0.3	
Vxz	0.3	
vyz	0.256	
Gxy	93.9707722	MPa
Gxz	93.9707722	MPa
Gyz	1182.00868	MPa
Xt	1584	MPa
Yt	1948.07744	MPa
Xc	661.5	MPa
Yc	1725.44002	MPa
SC	32.7376406	MPa
p	1.73	g/cm3

Figure D.2: Obtained data.

D.2 Chamis Abbreviations

D.2.1 Properties

E= *Modulus of elasticity*

G= *Shear modulus*

v= *Poisson's modulus*

X= *Breaking strain*

S= *Breaking shear stress*

ρ= *Density*

V= *Fiber volume fraction*

D.2.2 Subscript

L= *Longitudinal*

T= *Transversal*

LT= *Longitudinal-Transversal (xy)*

TT= *Transversal-Transversal (yz)*

t= *Traction*

f= *Fiber*

m= *Matrix*