Thesis for the Degree of Master in Science (Two Year) with a major in Textile Engineering

The Swedish School of Textiles

2016-06-05

Report no.

KNITTING OF CARBON AND DYNEEMA® FIBRES TO FIT FOR CONTOUR SHAPES IN COMPOSITES

Sharath Panduranga Shahu

TEXTILHÖGSKOLAN

HÖGSKOLAN I BORÅS

Visiting address: Skaraborgsvägen 3, Postal address: 501 90 Borås

Website: www.hb.se/ths

ACKNOWLEDGEMENTS

I would like to thank and appreciation given to the Swedish school of textiles for making this project visible and Social welfare department, India for making me visible.

I would like to thank Anders Person who helped me with his ideas to pursue my work and a special thanks to my supervisor Sunil.Kumar.Ramamorthy, who took a meticulous on my project.

I would also be very thankful for knitting lab technician Tommy Martinsson and polymer lab technician Haike Hilke.

Thanks for my family, friends and brother who bolster me each and every day to complete my Master of Science in Textile Engineering.

Sharath Panduranga Shahu

Borås

June, 2016

Abstract

Textile process and textile structures that are suitable for composites are carefully studied and chosen to have weft knitted fabrics. The aim of this research is to knit the carbon and Dyneema® fibres in circular weft knitting to fit contour shapes. Carbon/Dyneema® can also be knitted in warp knitting machines to get properties in multi axial direction. But the fabric was flat and can be used only for 2D shape products which are having less drapabiity. According to previous research, weft knitting is the best suitable for complex preforms. Before knitting these fibres properties were studied in order to avoid the damage to the carbon fibres. The carbon fibres have high bending rigidity, low resistance to friction and are very brittle. A small damage to the carbon fibre in knitting subsequently affect directly on the composite properties. The strongest manmade fibre manufactured till date is Dyneema® and these fibres could be used in composites due to its performance, properties and light weight. But, the Dyneema® fibres are expensive when compared to common polyester, so polyester fibres are used to compare the properties and cost performance ratio.

The critical bending of the carbon fibres causes friction between the fibres and also between fibre and machine. This was considered carefully during the knitting of carbon fibres and the idea chosen is mentioned in this thesis.

Between the two layers of Dyneema®/polyester, carbon fibres are laid circularly in unidirectional and in un-crimped condition. This makes the carbon yarn to possess good mechanical properties. The 2 layers of Dyneema®/polyester fibres exchange the loops at certain points to increase the inter-laminar strength and decrease the carbon fibre distortion. This structure helps to withstand external load. It is also lighter than the carbon composite with additional properties. This makes much more space in the future for the Dyneema® fibres in the 3D carbon composite manufacturing. The internal carbon fibres are fully covered by the Dyneema® fibres to withstand the external impact load and not to damage the carbon fibres. So the loop length, stitch density, fibre volume fractions are considered before knitting.

Keywords: Knitted fabrics, Dyneema® fibres, carbon fibres, Rib structure, in-plane, out of plane.

Popular abstract

The carbon fabric with many layers makes the carbon composite heavier and less usable in some light weight applications. The carbon knitted or weaved fabric has only carbon fibres and very brittle to So, I have chosen a Dyneema® fibre to mix along with the carbon fibres. The cost of carbon fibres and Dyneema® fibres is obviously very high; hence I compared cost performance of polyester and Dyneema®. A Dyneema® fibre is having low density than the carbon fibre and high impact resistance property. Dyneema® fibres are widely used in high performance applications like body armour, ropes to lift heavy load etc.

The aim of my thesis is to investigate and implement the knitting technique to knit the carbon and Dyneema® fibres. In composite manufacturing knitting technique could be used for producing reinforcement for several applications like the weaving and braiding. For instance knitting has good extensibility to shape for 3D structures whereas weaving need acumen cutting and takes more time for mounting.

In this work, carbon/ Dyneema® and carbon/polyester knitted fabrics were produced. These fabrics were reinforced in a matrix to produce composites. Fibres and composites were tested for mechanical properties. Lightweight circular/cylindrical prototypes were produced where the knitted fabric acts as an outer protective wall and polyurethane foam fills the inner cylinder. The knitted fabric is dipped in a resin bath along with the bladder and placed inside the mould. Then sufficient amount of foam is sprayed inside the mould from one point with some water. This helps in expanding the knitted material along with foam and takes the shape as mould. Further ideas and explanations of this are reflected in future research section at the end.

List of Abbreviations and symbols

€ - Euro

®- Registered trademark

°C – Degree in Celsius

1K - 1000 filaments

2D – 2 directional

3D – 3 directional

A - Planar area of the composite over which wale and course are measured

ASTM – American Standard Test Method

C- Course length / Course

CAD – Computer Aided Design

C_d – constant 9 X 10^5

C_s- System compliance

Db – Deci bel

DTex- DeciTex

D_y – Linear density of the yarn

Gms - Grams

GPa- Giga Pascal

Hz – Hertz

J – Joules

Kg/m^3 - Kilograms per cubic meter

KN- Kilo Newton

LS – Length of the yarn in one loop

Mm – Millimetre

MPa – Mega Pascal

Nk – Number of knitted fabric layers in one composite

P- Extension

PE – Polyethylene

P_f – Tensile strength of reinforcement fibre

t- Thickness of the composite

Tc – Crystallization temperature

Tex – 1000 meters of yarn weighing in 1gms

Tg- Glass transition temperature

Tm – Melting temperature

U- Curve up to failure

Vf – Fibre volume fraction

W- Wale length

W- Wale length / Wale

Π – 3.142

ε -Strain

σ - Stress

1 Introduction

During the last decade carbon composites manufacturing are growing rapidly in several fields such as marine, automobile, aerospace, wind turbines and defence. In the composites synthetic fibres like carbon, glass, aramid, and polyethylene are used. Generally the fibre is about 40-50% of the composites. The composite properties are governed by fibre properties, matrix properties and fibre-matrix interface properties. The fibre phase may be in the woven, nonwoven, chopped fibres, braided or knitted fabrics. The matrix phase is polymer resin such as epoxy resins in the composite material (Bagherpour, 2012).

The carbon fibre is considered to be strong, light weight, anti-corrosion, long lasting and capability to withstand high temperature (Park, 2015). Dyneema® fibres have high impact strength and it has high tensile strength. The woven, nonwoven and braided carbon composites combined together with other fibres have well in plane properties like shear stress, tensile stress, compressive stress, but poor out of plane properties like flexural loading and impact loading (J. G. H. Bouwmeester, 2008).

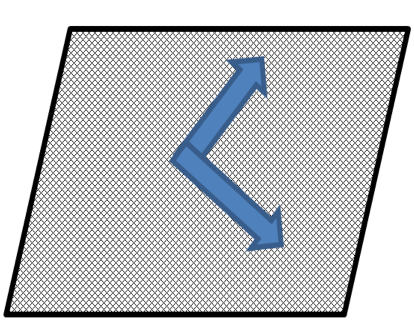


Figure 1 showing weaving has only in-plane properties; high stiffness and strength

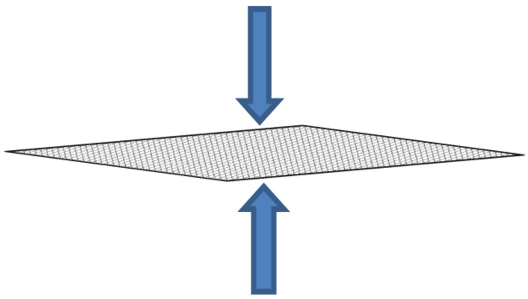


Figure 2 showing knitting has out-of-plane properties as well as in-plane properties; high impact loading and flexural loading

The knitting technique has well out of plane properties as well as in plane properties. Among the knitting methods, weft knitting plays a major role in changing the mechanical properties of the composites compared to warp knitting. A knitted fabric has a yarn orientation in out of plane direction due to interlooping of the fibres either in the wale direction or course direction makes the fabric stretchable. Hence the knitted fabric has a good out of plane properties as well as in-plane properties as shown in figure2. Hence, knitted fabric is best suitable for composite applications (Jorg MAYER, 1999). Due to these reasons knitting technique could be used in the composites.

The challenge for this work is to knit Dyneema® and carbon fibre, in which one is flexible fibre and the other is stiff fibre. Due to high bending rigidity of carbon fibres some of the machine and fabric parameters are considered before knitting, and it changes from machine to machine (Mădălina ZĂNOAGĂ, 2014). The micro damage upon bending causes the carbon fibres to lose its properties and it is directly effect on quality of composites. Several composite properties are considered such as impact resistance, flexural resistance and abrasion resistance before manufacturing. (Jorg mayer, 1999).

Carbon and Dyneema® fibres are used as reinforcement whereas epoxy as matrix in the composite preparation. My aim is not only to knit one stiff fibre along with flexible fibres but also to meet the mechanical requirements needed for 3D composites i.e., in plane and out of plane properties as stated above (Amnon, 1995). Inclusion of Dyneema® fibres provide good impact resistance and will be light weight (Christian Heiss, 2012).

The woven composite materials manufactured using carbon and Dyneema® fibres were tested for impact falling dart test in the ICAS (International Congress of the Aeronautical Sciences) article. The test clarifies that Dyneema® fibres can withstand the load even after the breakage of carbon fibres without losing its property. This means primary load is carried by carbon fibres and then secondary load by Dyneema® fibres (J. G. H. Bouwmeester, 2008). This makes it more interesting in further research and possibilities to manufacture the composite from knitting technique using the carbon and Dyneema fibres.

The weaving, nonwoven and braiding have a good in plane properties in multi axial and unidirectional hence it is used in 2D composites and not used in 3D composites. The latest technology; 3D orthogonal carbon weaving technique that is in the market is used to weave directly 3D shapes using carbon fibres. This technique is used to stitch the fabric in the thickness direction. But the layers are stitched by passing the needle and this makes the disastrous to the carbon fibres (Alagiruswamy, April 2006).

The woven plain fabric with only carbon fibres is said to have less impact resistance property and poor delamination resistance; when we apply force in the Z direction or thickness direction. But, the knitted fabrics have good elastic properties to cover the curved structures, good drape ability and high impact resistance properties (Miquel, 2014). In the Ray. (2011) article, reported that the knitted structures used in composites can withstand high impact resistance and load bearing capacity in all direction.

2 Literature review

2.1 Textile fibres

There are different natural and manmade fibres in the market. The textile fibres used in everyday application like clothing curtains and chairs. The fibres which are used for this work are mentioned below in detail with their properties and the end applications.

2.1.1 Carbon fibres

Carbon fibre is an isotropic material which is manufactured from petroleum pitch. The density of the carbon element ranges from 1.780 - 2.268gms/cm^3. The density of the carbon fibre varied upon precursors used during manufacturing and thermal treatment given for the fibre after manufacturing. Atomic structure of carbon fibres consists of carbon atoms arranged in hexagonal pattern as shown the figure 5. The carbon fibres are good conductors of electricity and hence care must be taken during carbon knitting (Chawla, 2012).

The carbon fibres that contain 92 % weight of carbon compound and 99.9% of carbon molecules within it. They can be crystalline, amorphous or partially crystalline. The crystal structure obtained from the crystal form and contains sp2 hybridised carbon atoms which arranged only in X and Y direction. The structure itself is having good properties in in plane direction i.e. x and y direction, but poor properties in thickness direction (Z) as shown in figure 5 (Huang, 2009).

The carbon atoms are bounded by 1) Covalent bonds by sp2 orbitals 2) Metallic bonds by P^2 orbitals. Here, Vander Waals forces in between each layers slides the carbon fibres and hence it conducts electricity and insulates thermal energy. Carbon fibres are manufactured by continuous stretching and heating process by the use of suitable precursor fibre (Chawla, 2012).

Carbon fibres can be manufactured from different precursors such as polyacrylonitrile, petroleum pitch or rayon. The different precursors give different properties so, suitable one is selected among them depending on the end uses (Yexiong Qi, 2015).

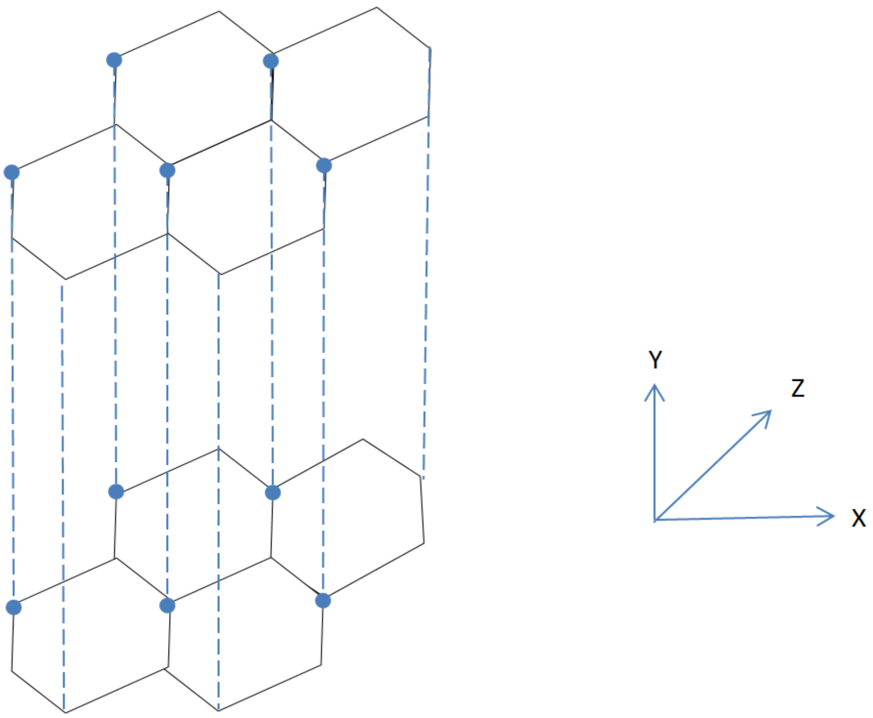
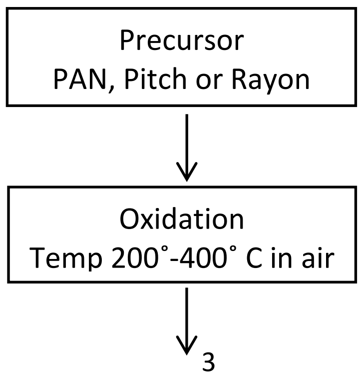
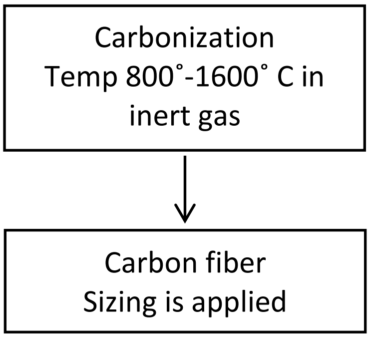


Figure 3 Crystal structure of the carbon fiber

2.1.1.1 Manufacturing process of carbon fibres





Flowchart 1 Carbon fiber manufacturing process

The precursors like Polyacrylonitrile (PAN), pitch or rayon are selected on the basis of the properties required. The precursors are heated up to 400˚C in air called oxidation process. The heated continued up to 800˚-1600˚C and nitrogen gas is passed to remove all the volatiles. In this process the carbon fibres are aligned straight carbon fibres are ready for next process. During manufacturing the carbon fibres are stretched to a high level to get good properties and high modulus. Nowadays carbon fibre production has increased as the carbon fibres are used as reinforcement material in advanced composite due to its good mechanical properties. The high bond strength in between the material signifies that modulus of the material is high and the Vander Waals force signifies they are less modulus material (Park, 2015).

2.1.1.2 Properties of carbon fibre

The carbon fibres are commercially available from low modulus to high modulus fibre depending upon the end uses. The table 1 was copied directly from the article written by Salar Bagherpour showing different kind of properties with different fibres (Bagherpour, 2012).

Table 1 Different kind of fibers with different properties

Sl no	Fibres	Density (kg/m^3)	Modulus (GPa)	Strength (MPa)
1	Carbon high strength	1.8	230	2480
2	Carbon high modulus	1.9	370	1790
3	Carbon Ultra High modulus	2.1	550 - 620	1030 - 1310

The properties vary from high strength carbon fibres to the ultra-high modulus fibre. The selection of these properties depends on the end applications and varied during processing (Bagherpour, 2012)

2.1.1.3 Carbon fibre manufacturing companies in the world

- Toray team in Japan
- Toho Tenax in USA
- Mitsubushi Rayon in Japan
- Formosa in Taiwan

- Hexcel in USA
- SGL in Germany
- Aksa in Turkey
- Cytec in USA
- Hyosung in South Korea
- Taekwang in South Korea (Park, 2015)

Carbon fibre production is increasing every year and it is used in various applications and the production is expected to reach twice by 2020 (Park, 2015).

2.1.2 Dyneema® fibres

Dyneema® is the family of Polyethylene and it is considered as the strongest manmade fibre till date. During spinning operation the molecular orientations are aligned, stretched parallel up to 95% to attain 85% crystallinity. Dyneema® is a class of Ultra High molecular Weight Poly Ethylene fibre (J. G. H. Bouwmeester, 2008). It is light weight, possesses high tensile strength, low density, high modulus, less elongation, high cut resistance and capability to withstand high impact (Anand, 2000).

2.1.2.1 Properties of Dyneema® fibres

- Density (kg/m^3) - 1.70 – 2.26
- Modulus (GPa) – 99
- Tensile strength (MPa) – 3200
- Diameter (μM) – 7- 10
- Maximum elongation % - 3.7%

These classes of polyethylene fibres are having high specific strength and hence using it in tensile loading applications. Dyneema has the Glass transition temperature (Tg) from -20° to 0° C, hence at room temperature PE is in rubbery material and upon stretching acts as viscoelastic material. This special feature makes the fibre tough and resistant to impact damage (Bagherpour, 2012). A Dyneema® fibre solely is having less compressive strength to use it in several applications. Hence, Dyneema® fibres can be combined with carbon fibres to make the composite strong using fabric manufacturing techniques (J. G. H. Bouwmeester, 2008).

The carbon and Dyneema fibres are costly to manufacture composite and to use it in several applications. So, in this work polyester fibres are used in place of Dyneema to compare the properties and cost performance ratio. When compared to polyester fibre, the Dyneema® fibre is expensive and the properties vary largely; that is needed for advance applications. The composite made up of only carbon fibre reinforcement possess less impact resistance (Bagherpour, 2012). Hence Dyneema® and carbon fibres were combined in this work for composite applications.

2.1.3 Polyester fibres

The raw material used for the manufacturing of polyester is crude oil. The polyester consists of long chain of repeating organic compounds of ester groups –COO- and generally called as PET (Poly Ethylene Terephthalate) fibre. This is manufactured by esterification process by the reaction of carboxylic acid and alcohol which gives ester compounds. This process is continued with a elimination of small amount of water molecule and carried in presence of heat. This process is called condensation method (Lin).

2.1.3.1 Properties of polyester fibre

- Density (kg/m^3) - 1.38
- Modulus (GPa) – 5.8-11.1
- Tensile strength (MPa) – 580-800
- Diameter (µM) – 7- 10
- Maximum elongation % - 20-50%

2.2 Knitting

Knitting is one of the manufacturing techniques to produce a fabric by interloping of the yarns either in the wale direction or course direction. Knitting is generally classified into warp knitting and weft knitting based on knitting direction. The yarn movement with respect to the direction of the fabric decides whether it is warp or weft knitting. The yarn movement in direction to the width or course of the fabric is called weft knitting and the yarn movement in wale direction or perpendicular to the width of the fabric called warp knitting as shown clearly in the figure 4 (Ray, 2011).

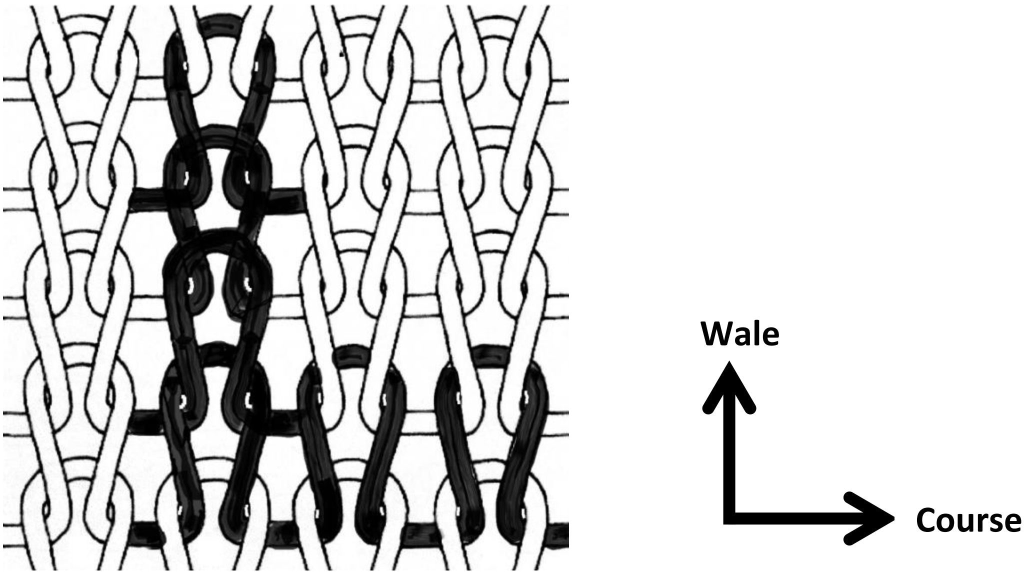


Figure 4 Knitting structure showing knitting direction in wale and course direction

Knitted fabric has properties that make them to use it in composites. However, the main advantage is that the complex composite structures can be tailored. They can also have good laminar force in thickness direction. The stich or space in the thickness direction is directly proportional to the distance between the needle beds (Dorin Ionesi, 2010).

The basic knitting textiles presently called as 2D textiles and using it as 3D clothing for engineering applications. If the knitted fabric to be used in engineered applications then we need 3D structures not 2D structures (Y. Liu, 2015).

Knitting was art for the people in olden days then the technique to be used in garments to make sweaters, t-shirts and other clothing. This technique can also be used in composites and to make it more susceptible for technical purpose; knitted fabric is having good out of plane properties and in-plane properties (Sandip Mukherjee, 2014).

Advantages of knitting in composite applications are

Knitted fabrics allow complex 3D shapes

Fabric handling is easy during processing

Easily process ability of high performance fibres

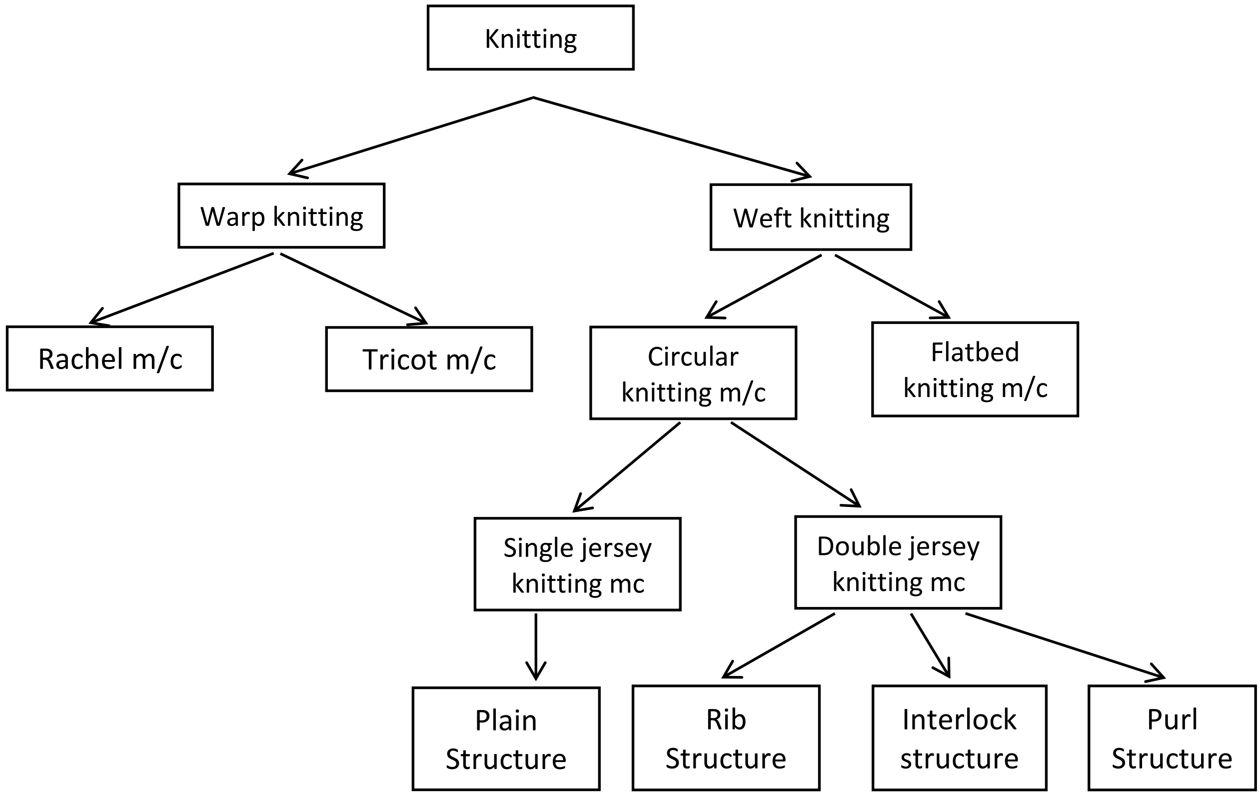
Seamless composites give the even properties and no resin accumulation occured

Short intervals of production

Fibre arrangement can be tailored easily while processing (Mădălina ZĂNOAGĂ, 2014)

In the above knitting types weft knitting plays a major role in composite applications due to its excellent formability. As reported by Tianmei Zhong and Hong Hu (2007), formability is the ability of a planar textile structure to be directly deformed to fit for three dimensional surfaces without the formation of wrinkles or kinks. This formability increases the production by eliminating the cutting time and improves the mechanical properties of the composite.

2.2.1 Classification of knitting



Flowchart 2 Classification of knitting based on knitting types, knitting machine and knitting structures

2.2.2 Weft knitting machine

In weft knitting the loop formed in the wale direction or across the width of the fabric. The weft knitting technique is used in 2 kinds of machines i.e. circular weft knitting and flatbed knitting machine (Carmaine Mozza, 2001). In circular weft knitting the needle bed or machine is circular and fabric withdrawn at the bottom. Then the withdrawn fabric wind to the beam at certain tension. Usually the circular weft knitting is divided into two types based on needles and needle bed they are Single jersey machine and double jersey machine (Ray, 2011).

2.2.2.1 Single jersey circular weft knitting machine

The machine in which one set of needles arranged on the groves or needle bed is called single jersey machine or plain fabric knitting machine. (Ray, 2011). Mostly, this machine uses only the latch needle but very few machines also have compound needles. The needles are fixed on the needle bed in single jersey machine and cams are fixed to bearing called cam frame. In this machine the needle bed is moving circularly keeping the cam frame stationary. The needle and cams are changed by just opening the screw on the top of the cams. (Carmaine Mozza, 2001)

2.2.2.2 Double jersey circular weft knitting machine

The machine in which two set of needles arranged on the groves or needle bed is called double jersey machine. In this machine we can knit the plain fabric by inactivating the upper bed of the needle. (Ray, 2011). Here, the needles on the circular bed is fixed circularly called "Cylinder" and the other set of needles present right angle to that cylinder needles called as "Dial". Both latch and compounds needles used in this machine, but dominating needles are latch needles in the single jersey machine. The double jersey machine can be used when a continuous fabric has to be manufactured, the cam frame will be rotating and the needle bed is kept stationary. In the same machine, cam frame can be kept stationary and needle bed rotating. (Carmaine Mozza, 2001)

2.2.3 Knitting structure

These structures play a major role in changing the properties of the fabric in end applications such as in composites. So the proper choice of structure, knitting technique is very important and explained in detail below.

Plain structure

Plain structure is produced in single jersey machine and it is produced by single set of needles. It is quiet open structure and poor mechanical properties compared to double jersey (Ray, 2011).

Rib Structure

Rib structure is produced in Double jersey machine and it is produced by two set of needles. Rib structures are produced by double jersey machine using rib gating. It appears similar on both sides; face and back side. Fabric stretches in width wise and has moderate dimensional stability. The balanced rib structure may be 1X1, 2X2 and unbalanced structure are 2X1, 3X1, 3X2 etc. (Ray, 2011).

Interlock Structure

Interlock structure is produced in Double jersey machine and it is produced by two set of needles. Interlock structures are produced by double jersey machine using interlock gating and also by rib gating. The loops are locked to stretch the fabric; extension of the fabric changes the internal structure (Ray, 2011).

Purl Structure

Purl structure is produced in double jersey machine and it is produced by two set of needles. Purl structures are used to produce plain structures and rib structures if required. Fabric stretches in length wise and loops appear to be in width wise (Ray, 2011).

2.2.4 Basic knitting fabric, machine parameter observed and considered

Machine parameter

- Machine speed
  Higher the machine speed higher the friction and yarn feeding speed should also be high.
- Gap between the two needle beds
  Lower the needle bed distance higher the friction and high chance of carbon fiber coming out
- Increase fiber volume fraction
  Increase in Dyneema® fibers decreases the weight in carbon composites and withstand high load / impact.
- Fabric take down speed
  Increase in speed makes the fabric to stretch more or variation of tension at different points causes the carbon fibre to bend.
- Yarn guides and creel system
  In this work, experiment we eliminated creel system and passed carbon fibers in only one guide.

Fabric parameter

- Fiber count / tow size
- Frictional co efficient of carbon to Dyneema® fiber
- Yarn feeding tension
- Stitch length / loop length
- Design and structure
- Stitch density

2.3 Composites

Composite can be defined as the combination of 2 or more materials that results in better properties than the individual material. Generally, the two materials are matrix and reinforcement as shown in figure 5. Some of the composites are manmade and some of them are naturally available. The different types of composites already exist like sand-rock, cement bricks, wood-pigment etc. Cement pillar is the good example for composite, here the iron or steel rods used as reinforcement and cement mixed with water as a matrix. The property of pillar is better than the individual material and withstands load (Murali Krishna Yantrapati, 2015).

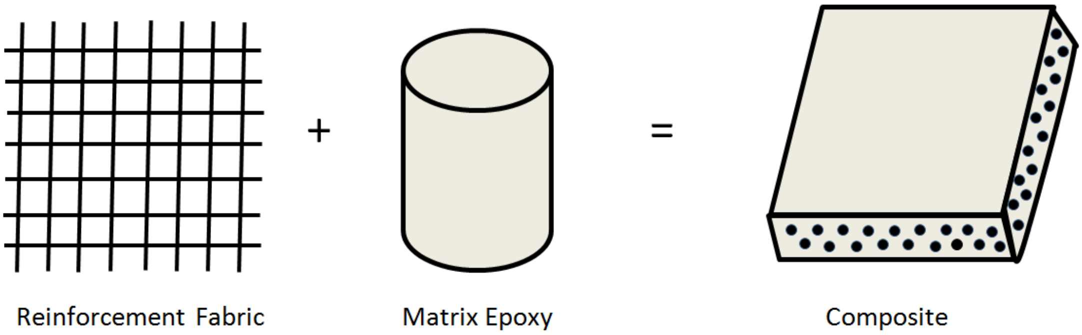


Figure 5 Composite preparations from 2 different materials

These composite materials are being used in aerospace applications for last 3 decades to make the planes light weight. The 2D and 3D composites are also used nowadays to replace heavy metal parts. The most common properties of composites are light weight, high stiffness and strength, good damping, corrosion resistance, durability etc. (Murali Krishna Yantrapati, 2015).

Some of the limitations of composites are high cost, less damage tolerance, less impact and abrasion resistance property. Still many researchers are trying to overcome these limitations and make the composite 100% perfect for best specific applications (Miravete, 1999).

2.3.1 Selection of reinforcement fibre or fabrics

The reinforcement material are short fibres, long fibres, whiskers, fabrics (woven, non woven, knitted) and particulate. The reinforcement provides strength, stiffness and it is mostly stronger, stiffer compared to matrix (F.C.Cambell, 2010).

The fibres that have been used in my thesis are mentioned and its properties were explained in the section 2.1. Impact resistance properties of Dyneema® are high whereas, the stiff carbon fibres make the carbon composite material to increase the tensile properties. The aerial weight of the product mainly depends on density of carbon fibre and Dyneema® fibre, fabric construction, number of loops per inch. If the fibres aligned in only one direction then it takes load along the direction of the fibre. Similarly bi-axial, tri-axial, multi-axial fabrics are manufactured using warp knitting method. For example unidirectional fabric can be layered one above the other in any angle or 0°, 90°, +45°,-45° to withstand the load in the particularly required direction (J. G. H. Bouwmeester, 2008). But this technique is not in practice because we cannot tailor the composite material depending upon the properties required.

According to a survey regarding unidirectional and other axial fabrics, the idea is to make a composite cheap and feasible for tailoring of the properties. Advanced composite materials with textile preforms and complex structures or shapes are used to replace conventional composites like plastics, steel, glass, films, paper or wood (Dorin Ionesi, 2010).

2.3.2 Types of reinforcement material or 3D textile process used in composites

Particulate reinforcement

- Silica compounds
- Metallic compounds
- Plastic whiskers
- Rubber

Fibre reinforcement

- Glass fibres
- Carbon fibres
- Boron fibres
- Aramid fibres
- Dyneema® fibres
- Other polymeric fibres
- Metallic fibres
- Ceramic fibres (Akovali, 2001)

Fibre forms

- Weaving
- Braiding
- Woven chopped
- Mats
- Knits
- Roving's
- Preforms

2.3.3 Selection of matrix

The matrix is polymer, ceramic or metal. The matrix may be either thermoset or thermoplastic material and will be in discontinuous phase, hence spreads overall the composite material. The matrix holds the reinforced material in a place, protects from abrasion and environment (F.C.Cambell, 2010).

Each composite properties depends on

1) Individual component properties

2) Ratio of the different phase materials

3) Degree of orientation

4) Adhesive properties between the matrix and reinforcement

5) The size, shape and space occupied by each components

These are all the properties to consider to design a composite material and to tailor the properties as per requirement (Bagherpour, 2012).

2.3.4 Fibre volume fraction (V_f)

The knitted fabric composite consists of the resin and the reinforcement fibres. So it is very crucial to find the fibre or resin volume in percentage and calculated by

$$V_f = \frac{n_k D_y L_s \, C \, W}{C_d P_f \, A \, t} \quad \text{(Eq.1)}$$

Where,

n_k – Number of knitted fabric layers in one composite

D_y – Linear density of the yarn

L_S – Length of the yarn in one loop

C- Course length

W- Wale length

C_d – constant 9×10^5

P_f – Tensile strength of reinforcement fibre

A- Planar area of the composite over which wale and course are measured

t- Thickness of the composite

The fibre volume fraction mainly depends on the D_y (Linear density of the yarn), stitch density of the knitted fabric (C X W) and n_k (Number of knitted fabric layers in one composite) (Chou, 1996).

2.3.5 Epoxy

The epoxy is a simple 3 member group called as epoxides. It consists of 1 atom of oxygen and 2 atoms of carbon in the ring. Usually the resin is a low molecular weight compound. There are different kinds of epoxies available in the market. The resins are selected for composite preparation depending upon the end application. Some resins are acidic and some are basic depending on this the curing is performed (Akovali, 2001).

Advantages of epoxy

- Low shrinkage during cure
- Less volatile and mostly contains pure polymer compounds
- High resistance to chemicals and all kind of weathers
- High adhesion properties for different materials including fibres
- Good electrical properties (Akovali, 2001)

2.3.6 Seamless composite parts

Different manufacturing method to produce seamless parts with some characteristics, limitations and product properties are listed below.

Circular weft knitting

As mentioned earlier in section 2.2 the circular weft knitting. This produces a circular seamless fabric in width direction to the machine and without any end in the length direction to machine. Different width or circumference of the fabric is manufactured depending on the end uses.

Filament winding

This process is very simple in which a band of continuous filaments are wind around the rotating mandrel. The mandrel is a heated so that it can cure the matrix easily once the filament is wind. This process consists of wet winding and dry winding. In the wet winding the filaments passed are pre impregnated with the resin to pass to mandrel and then cured at certain temperature. In dry winding the filaments passed without any impregnate in the resin, but the whole mandrel is dipped to impregnate and cured later. The mandrel is designed in the shape of composite required for end applications. The wet winding process is the widely used process in Industrial sectors. The winding angle can be varied upon the requirements. The products may be either cylinders, tubes and sometimes T shapes (Akovali, 2001).

Braiding

A filament braiding works on the same principle to the pole dance. In a pole dance a set of people move forward and backward in circularly holding the yarns below. Similar to this in braiding instead of people, bobbins are rotated. Then instead of pole, a smooth surfaced cylinder mandrel is used. It is similar to filament winding process and here the whole mandrel is rotated to feed to the braiding machine. Here the yarns are intertwined together to have a compact package. The fibres are passed under lot of tension hence, it can damage the carbon fibres; friction generated are very high (Akovali, 2001).

Pultrusion

It is a continuous process like filament winding and it is the only process which is automated. The production rate is very high and offers high fibre volume fraction with good quality products. This process is based on the transformation method; transferring from liquid to solid form. The continuous strands of filaments or roving's are pulled inside the resin bath and passed to the curing system, where it solidifies to get the final product. The starting material may be woven, roving, filament, knits, tapes etc. The care is taken to wet all the fibres by changing the resin viscosity (Akovali, 2001)

The knitted fabrics are used in 3D composite structures nowadays to increase the fabric performance. This work is focused on the weft knitting machines and its structures as the loop of yarns are formed in the width wise of the fabric. From the above study it justifies that which structure are selected, selected structural elements and mechanical properties needed. Finally manufacturing method and the possible applications is shown in the figure 6.

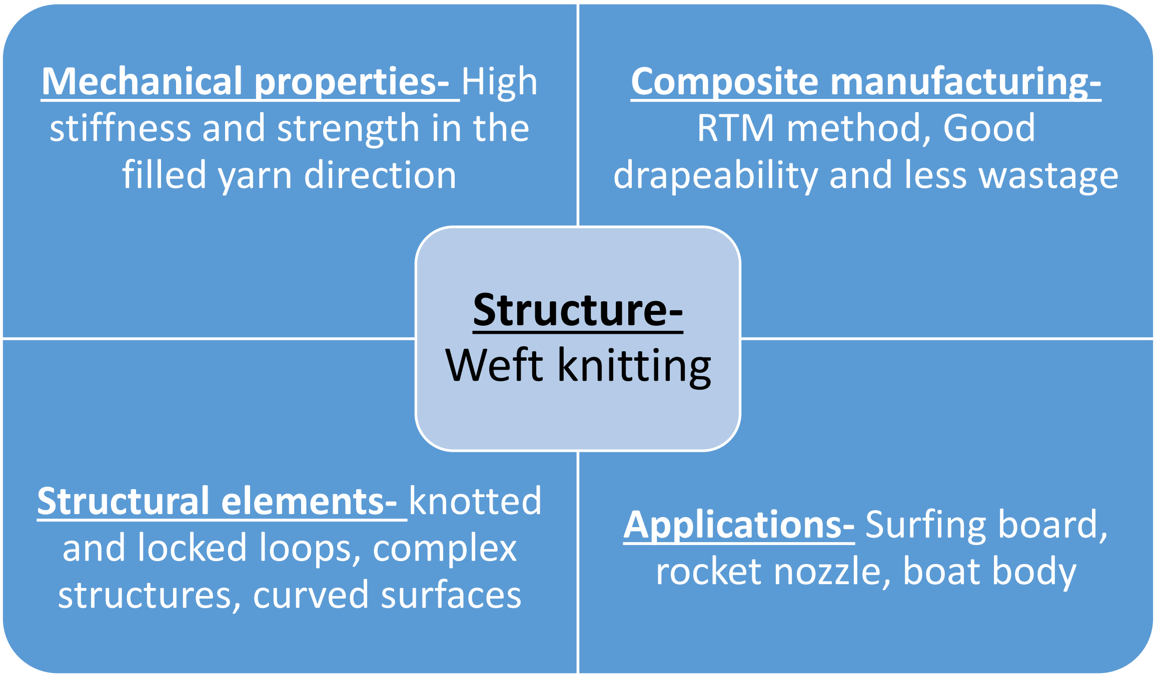


Figure 6 showing brief planning of my work from the above studies

2.4 Problem statement

2.4.1 Open structure

The study done by Christian Heiss, Nahum Travitzky and Peter Greil (2012), reported that it is very difficult to knit only the carbon fiber due to its brittleness and high modulus. They conjecture very clearly, that the final knitted fabric has good drapability and flexibility but open structure with damaged fibers at some points. The carbon fiber breakage may be due to improper sizing and more friction points while knitting (Christian Heiss, 2012).

2.4.2 Problem in thickness direction

The 2D composite materials consists of unidirectional fibers laminate oriented in different angles as shown in the below figure 7. Good stiffness and strength is achieved in the machine direction, but external loading cause's cracks and leads to failure of the composites. This problem arises because there are no fibers oriented in the thickness direction within the laminates. Studies have been focusing on 3D reinforcements to make composites preforms in 3directions. Knitting was one of the techniques used for 3D reinforcement structures.

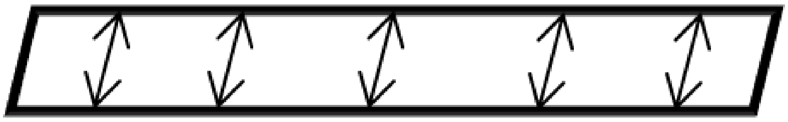


Figure 7 Cross section of the weaving fabric shows poor inter laminar strength

2.4.3 Research questions

Is it possible to knit stiff carbon and flexible Dyneema fibres without damaging the carbon fibres?

How well will the composite properties are affected upon changing the fibres and the fabric manufacturing technique?

Can blend carbon fibres and Dyneema fibres can be used in complex shape composites?

Will inclusion of Dyneema fibres increase the impact resistance of the carbon composites and also make the composites lighter?

Can polyester replace Dyneema fibre in terms of cost-performance ratio?

How well the knitted fabric stretches upon using the foam as core material in composite?

2.4.4 Objectives

To use circular weft knitting technology to design and manufacture a composite material that can be used in liquid natural gas containers or surfing boards

Inspecting the carbon fibre damage during weft knitting

Calculating the tensile strength, impact loading and thermal properties of the composite material

3 Experimental methods and procedure

Till now gained knowledge on selection of composite components, manufacturing methods and testing methods that are to be used in this work. The below sections explain how and why in this work used the different textile fibres, knitting method and composite preparation method.

3.1 Fabric processing methods

From the literature study on knitting techniques and structures, the double jersey weft knitting machine using rib structure is selected to knit the blend of carbon/Dyneema and carbon/polyester fabric. In this machine, one can knit the carbon fibre without bending and breaking just by laying in-between the two layers of the knitted Dyneema® or polyester fibres. These knitted fabrics were processed on circular weft knitting machine a manufacturer of German company Mayer and Cie.

The regular width of the knitted fabric in this circular weft knitting machine is 26 inches and can be decreased or increased depending on the order of the material. In my work the fabric is knitted with 26 inches as circumference. The stich or loop formation of carbon fibre is eliminated completely and it is just laid circularly. Some of the knitting elements like sinkers, needle bed, knock over blades, cams and guide bar are adjusted. Several factors considered are carbon fibre bending, friction between the carbon/Dyneema® fibres and carbon/ polyester fibres, head to head distance between the needles can be altered depending on tow size. The bobbins with carbon fibre held at certain height with certain tension to feed the carbon fibres.

Considering all the above factors the carbon/Dyneema® fibres and carbon/ polyester fibres were knitted using the single jersey circular knitting machine and double jersey circular knitting machine.

3.1.1 Single Jersey machine (Plain fabric)

This machine produced a simple plain fabric from one set of needles and open structure. For test method 1, every 4th yarn the feeder was changed to carbon fibres from Dyneema® fibres and the loop angle was changed. Similarly, for test method 2, every 8th yarn the feeder was changed to carbon fibres from Dyneema® fibres and the loop angle was increased. The two fabrics were tested for further consideration and tested.

3.1.2 Double Jersey machine (Rib fabric)

Double jersey machine has the double set of needles; two layers of fabric knit and exchanged the loops as per design shown below in figure 8a and 8b. Then the final design 8c is selected to hold the different fabric layers together with straight carbon fibres. The same carbon fibre and Dyneema® fibres are knitted in this machine but several parameters were considered before knitting. Guide rollers and guides are avoided for the carbon fibres to avoid the damages. So, the carbon spools were held on the 2 sides of the machine to feed the carbon fibre in the straight path to feeder as shown in figure 9. Here, the carbon fibre is just placed in between the two layers of the fabric as per knit structure. The design and pattern is loaded in the jacquard machine for the needle movement throughout the fabric. Out of the different designs, the final selection of the design was made in the design software. The more exchange points between the two layers of Dyneema® to avoid the separation of the fabric and bow effect.

Key focus-

- Change the structure to avoid the separation of the fabric and keeping the carbon fibre straight.
- Easy handling after knitting

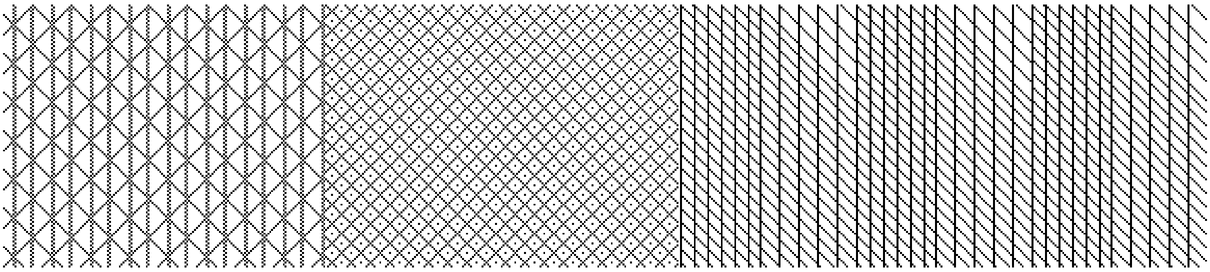


Figure- 8a Knitting design 1

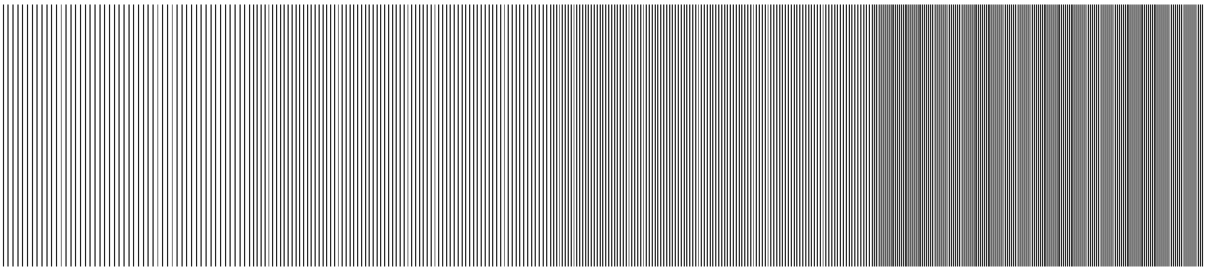


Figure- 8b Knitting design 2

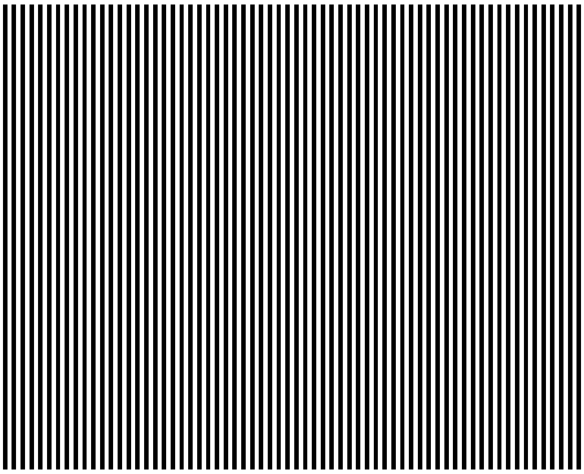


Figure- 8c final selected knitting design

Figure 9 Carbon bobbins are hold in hand to pass the yarns straight to feeder

Figure 10- Double jersey weft knitted fabric using rib structure: 1-Creel system; 2-Knitting system; 3-Fabric take down system

3.1.3 Biaxial, Tri axial knitting of carbon and Dyneema® fibres

In the above mentioned knitting technique, one can insert carbon fibre in only one direction and hence unidirectional properties can be attained. As stated in the article (H.Cebulla, 2002) the biaxial weft knitted fabric are in the direction of vertical and horizontal , in which the centre fibres are held together by the stitched yarn. The two layers of the fabric stitched at a certain point to keep the carbon fibre straight and to hold in place. This is only possible with the warp knitting machine and not with the weft knitting machine (H.Cebulla, 2002).

3.2 Preparation of composites

The knitted fabrics consist of polyester/carbon and Dyneema®/carbon fibres, and they were reinforced with resin by hand layup method. The epoxy resin is mixed thoroughly by epoxy (A) and hardener (B) in the ratio 2A:1B. For example, for 100gms of epoxy (A), 50gms of hardener (B) is added. The thermoset resin was commonly used to manufacture the carbon composites and hence used in my work. The mixed resin is applied in-between each layer.

It is important to not leave any chopped fibre and avoid waviness on lay-up of fabric; it could change the properties of the composites. The fabric is placed one above the other with a resin impregnated as shown in figure 11. Then the resin impregnated layers were placed under compression mould where 130kN pressure is applied. The compression moulding picture is shown in the below figure 12 and the curing was done at 80° C for 25 minutes. Four laminates were made in the thickness range 0.4mm; the length and width were 20 X 20cms.

The four laminates consist of four layers were manufactured and named shortly in the whole report as below

1a) Dyneema®/Carbon laid in unidirectional (0°)

1b) Dyneema®/Carbon laid in bidirectional ($0^{\circ}/90^{\circ}$)

2a) Polyester/Carbon laid in unidirectional (0°)

2b) Polyester/Carbon laid in bidirectional ($0^{\circ}/90^{\circ}$)

<u>Calculation from the</u>

From the several designs of the knitted fabric

Resin: Hardener ratio is 2A:1B

Dyneema® / Carbon –**unidirectional and bidirectional**

Weight of 4 fabric layers – 36gms

Resin (A) - 24gms

Hardener (B) - 12gms

Polyester/ Carbon – **unidirectional and bidirectional**

Weight of 4 fabric layers – 42.97gms

Resin (A) - 28.66gms

Hardener (B) - 14.33gms

Figure 11 Resin distributed equally on the fabric with a foil beneath

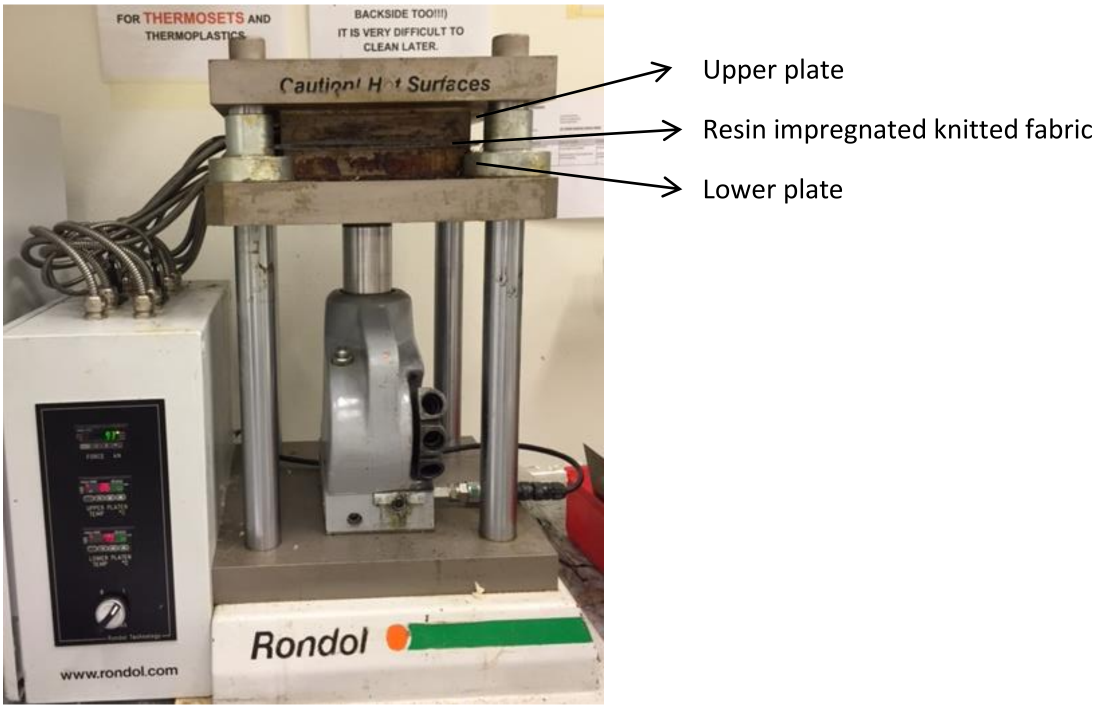


Figure 12 Compression molding machine with digital temperature and applied pressure display

3.3 Testing methods

Fibre Materials

In this work carbon, polyester and Dyneema® fibres are used to knit polyester/carbon and Dyneema®/carbon fabric.

The carbon tow size was 1K, polyester 110DTex and Dyneema® 110dtex. The carbon fibre was received from Schappe France and the other fibres from TST, Sweden.

3.3.1 Fibre tensile testing

These fibres are used in composites and undergo a lot of stresses when it is used in several applications like surfing boards. Hence, tensile testing was performed to find the modulus, strength, elongation and force at break.

Tensile tests were performed on the single filaments using the universal tensile testing as per ASTM D3379 standards as shown in the figure 13; crosshead speed was 0.5 mm/min and the load cell used was 250 KN. This test was conducted at different gauze length; 25 and 70 mm. A preload of 0.33cN of yarn is applied as per ISO (International Standard Organisation) standard. The fibres were gripped with upper and lower clamps or jaws for the testing. This test was conducted under standard laboratory room temperature $25 \pm 2^{\circ}$ C. Ten specimens were tested for carbon fibers, Dyneema® fibers and polyethylene fibers with both 25mm and 70mm gauze length (Kimiyoshi Naitoa, 2008).

Different clamps or grips were used for fibers, fabric and composites. Then modulus, elongation, force at break were analysed in detail and cost performance price ratios were calculated to compare the properties.

The price chart for each bobbin

Bobbin used	Carbon (1K)	Dyneema® (110dtex)	Polyester (110dtex)
Price in Euros (€)	250€	150€	95€

Table 2 Different kind of fibers with different price to calculate price performance ratio

$$Performance\ price\ ratio = \frac{Tensile\ strength(MPa)}{Price(1\ Bobbin)} \quad \text{(Eq.2)}$$

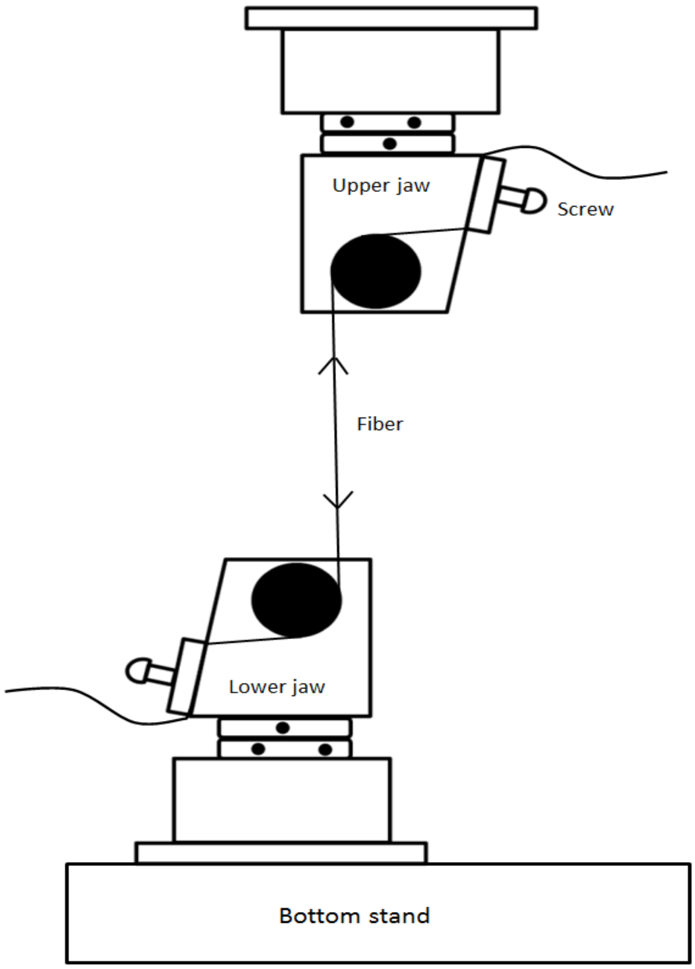


Figure 13 Tensile testing instrument with equipment's mentioned

This test gives load required to break the filament with certain strain. Stress (σ) and strain (ε) was calculated from the below formula

Formula-

The tensile stress (σ) and strain (ε) is calculated by the below formula

$$\sigma = \frac{F}{A} \quad \text{(Eq.3)}$$

$$\varepsilon = \frac{\delta}{L} \quad \text{(Eq.4)}$$

Where,

F – Force

A - Area

δ – length of stretch

L – Original length

3.3.2 Fabric testing

3.3.2.1 Single jersey circular knitting machine

Test method 1-

The fabric was tested visually for single jersey knitted fabric, the intention was not to break the carbon fibres, but the fibres were broken due to increase in loop bending. The picture clearly shows that the carbon fibres were broken due to bending and the fibres were not straight to carry the load. When, the carbon fibre percentage is decreased in the composite material; quality will decrease, fibres were held loosely, carries uneven loading.

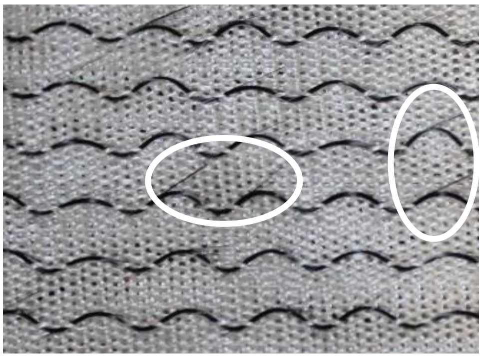


Figure 14 Single jersey knitted fabric on every 4th needle and circle showing breakage of carbon fibers

Test method 2-

The other possibility was to increase the loop angle and stitch number from 4th to 8th. Still the carbon fibres were broken at the knit point as shown in the figure. The carbon fibres are very brittle and clearly define that one cannot bend; I could not knit on the single jersey machine even after changing the structures. The figure shows the breakage of carbon fibre breakage at the point of knitting. This structure decreased the carbon fibre percentage is decreased and also the fibres were held loosely on the surface. The knitted fabric was very difficult to handle.

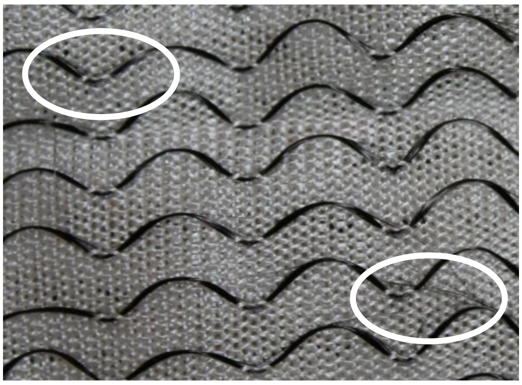


Figure 15 Single jersey knitted fabric on every 8th needle and circle showing breakage of carbon fibers

3.3.2.2 Double jersey circular knitting machine

Optical microscopic test-

The knitted fabrics were tested for fracture surfaces or filaments in optical microscope. This was done to investigate fracture or damage to the carbon fibres during knitting. Due to tension during fabric withdraw in knitting, handling and cutting cause the carbon fibre to bend. The below picture 16 a) Normal knitted fabric from the top view 16 b) Dyneema® fibres were removed slowly without disturbing the carbon fibres 16 c) Zoomed in for the carbon fibres.

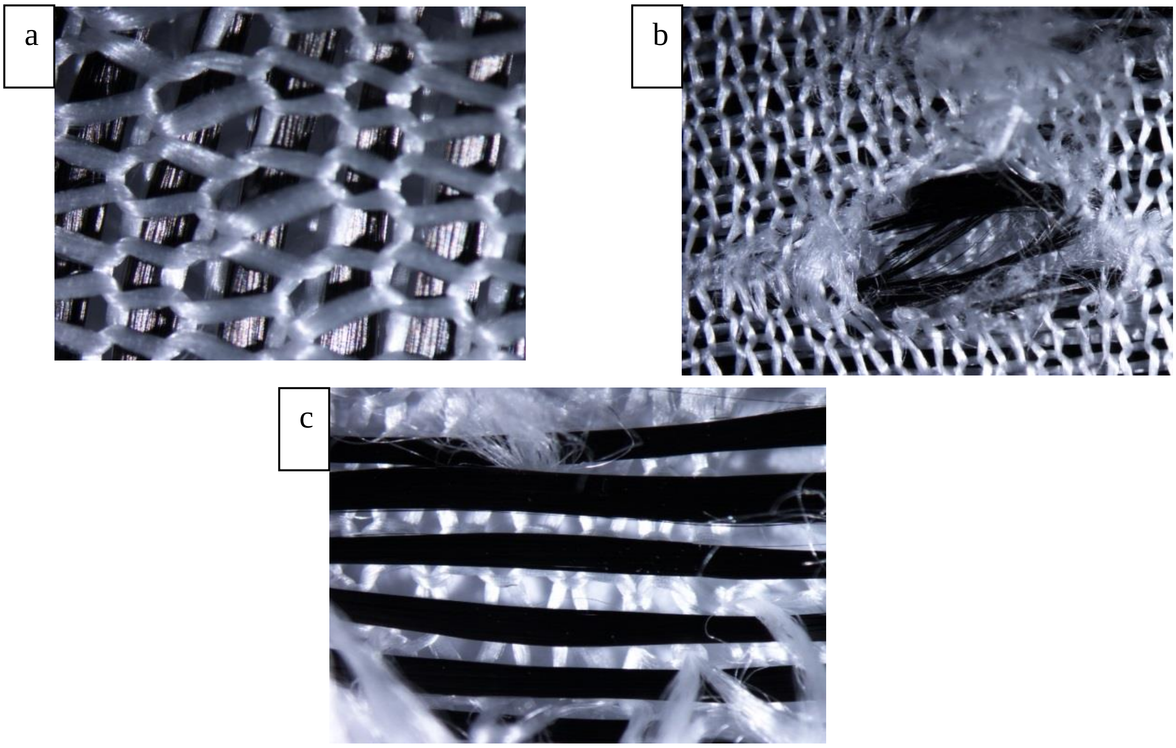


Figure 16 Microscopic test for knitted fabric a) Normal knitted fabric from the top view b) Surface/Dyneema® fibres were removed slowly without disturbing the carbon fibres c) Zoomed in for the carbon fibres.

3.3.3 Composite materials

Test samples were cut from the composite laminates according to international standards using water jet machine. Carbon composites are strong and therefore cut using water jet technology with good accuracy. The sample was cut along the direction of the carbon fibres oriented in the unidirectional composite. The cut samples were tested for tensile testing and impact properties.

3.3.3.1 Tensile testing:

Tensile testing was performed to find out the stress and the strain. The tests were performed in the universal tensile testing instrument according to ASTM D 638 standards, as shown in figure 17. All the specimens were tested at 0.5 mm/min crosshead movement and the load cell used was 10 KN. The tensile modulus is the curve shown in the graph and it explains that ratio of stress upon strain. The tensile strength was the final curve that measures the final breakdown of the filament. The sensor was attached to a load with a tight screw and it detects the specimen micro damage in dB (decibel) and sends signal in waves. The composite strip was gripped by upper and lower clamps or jaws and the test was conducted under standard laboratory room temperature 23 ± 3° C and 50 ± 5% relative humidity. Three specimens were tested for Polyester/Carbon and Dyneema®/Carbon layered composite. The stress-strain curve was generated for each test specimen; the average was taken and performance price ratio was also calculated (Kimiyoshi Naitoa, 2008).

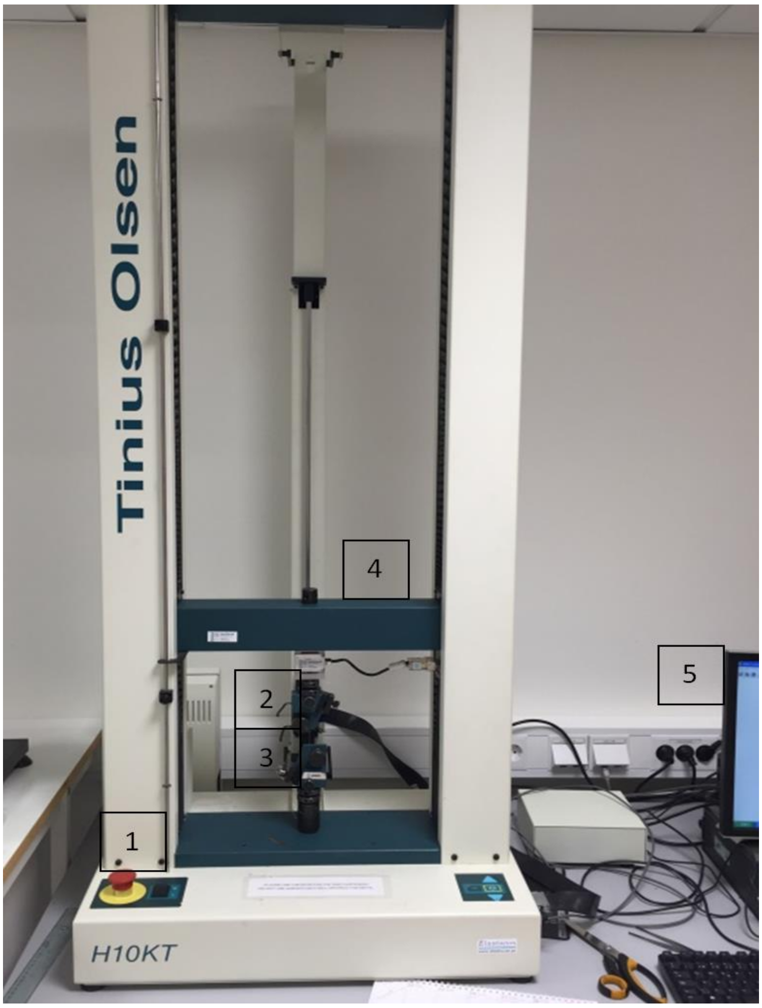


Figure 17- Tensile testing for composite with equipment's: 1-Power button; 2-Upper jaw; 3-Lower jaw; 4-Crosshead; 5-Computer display

Once the test is conducted the results were copied and compared with each other. The tensile strength was considered and calculated for price performance ratio for one bobbin.

$$Performance\ price\ ratio = \frac{Tensile\ strength(MPa)}{Price(1\ Bobbin)} \quad \text{(Eq.5)}$$

3.3.3.1 Impact testing:

Impact resistance is one of the main properties of the fibre reinforced composite. A load of certain free falling weight hit a sample and energy absorbed data was collected. The Figure 18 shows the impact testing machine with a load of 5J.

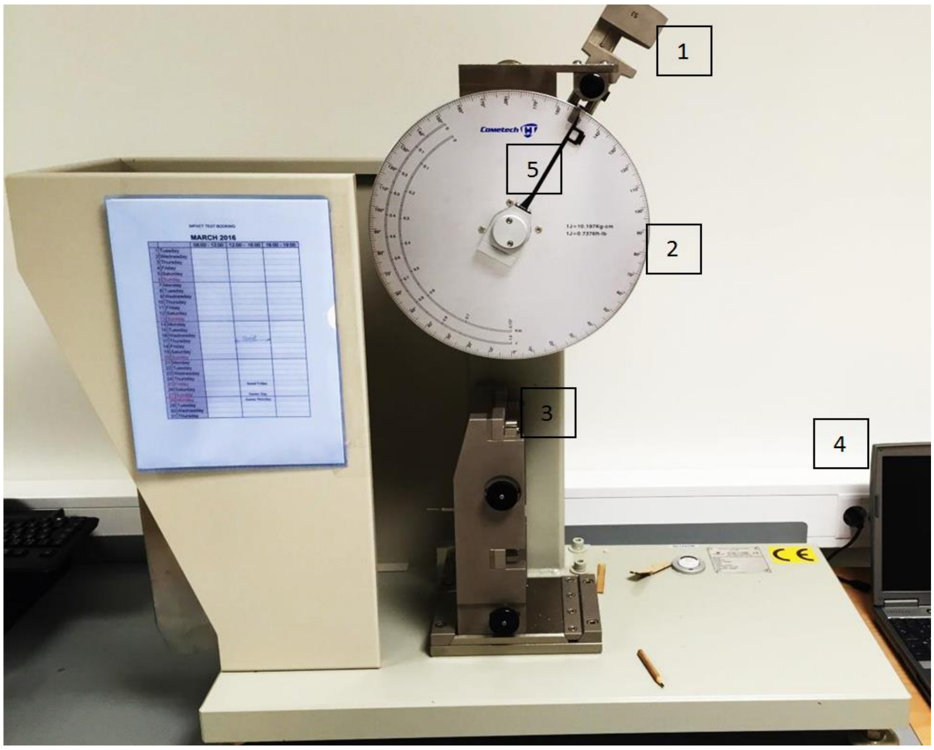


Figure 18- Impact testing instrument with equipment's: 1-5J weight; 2- Impact measuring scale; 3- Specimen mounting place; 4- Computer; 5- Needle.

3.3.3.2 DMTA

DMA800 equipment was to determine viscoelastic properties of the composites. The machine was calibrated before using the sample. The sample was tested using dual cantilever clamp and the sample length was 35mm length and 0.91 thick. The sample was protected by oval mesh to maintain the constant temperature throughout the test.
The Viscoelastic properties of sample were evaluated by DMTA, where a sinusoidal force (stress) is applied to a material and the resulting deformation (strain) is measured. As the composite are made of viscoelastic polymers, there will be a phase difference. This phase difference can be used to determine fundamental material properties.

Mechanical properties of the sample was measured as a function of temperature (-10°C to 160°C) with experimental rates of heating and cooling. At least 3 tests were done for each specimen.

Log method to conduct test

Fixture for fiber: l=56 mm, w=9.70mm t= 0.80 mm

Amplitude: 0.44 mNm

Frequency: 1Hz to 100 Hz

Temperature: -10 to +150°C

Temperature / ramp rate: 5°C /min

DMTA measures the polymer's mechanical properties as a function of time and temperature. Glass transition temperature (Tg) was calculated for the composite. As the glass transition will affect the mechanical properties of the composites.

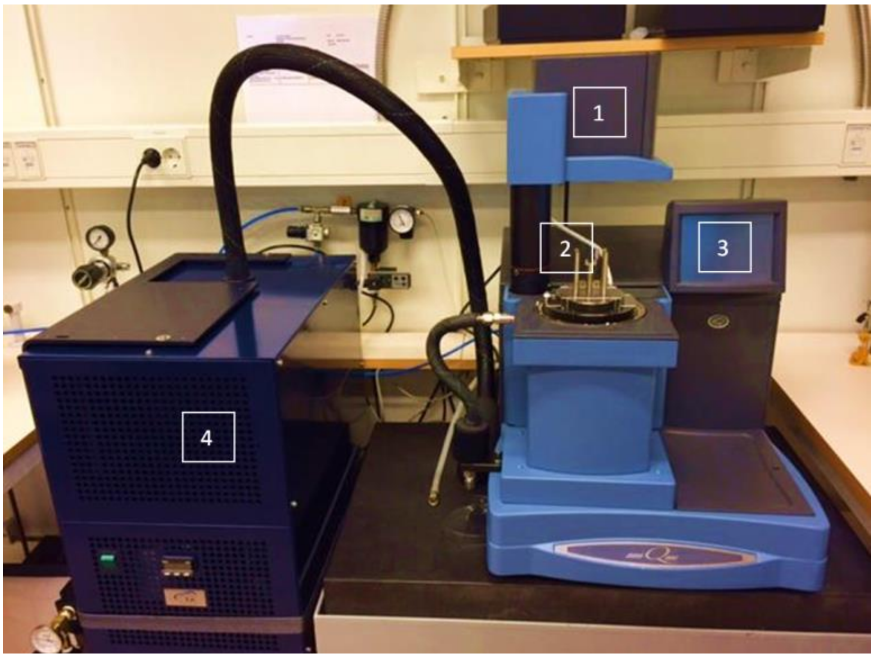


Figure 19- Experimental DMTA equipment with instruments mentioned in square box: 1- Furnace; 2- Dual cantilever clamp; 3- Display; 4- Cooling chamber with liquid nitrogen gas

3.3.3.3 DSC (Differential Scanning Calorimeter)

DSCQ1000 was used in this work. A small aluminium pan with the sample and an empty reference pan were placed on top of two individual heaters. The idea is that, as the content of the pans are different; they require different amounts of heat to maintain the same temperatures. The DSC measures the difference in heat needed as a function of temperature.

A small amount of composite was placed in the DSC pan and the pan was weighed both before and after the polymer sample was placed in it. The pan mass and the sample mass were noted. The composite sample was weighing approximately 15gms and the pan mass was approximately weighing 20gms.

The nitrogen gas was purged and used as inert gas for testing. The DSC machine was set to run the two pans in the programmed temperature cycles. The procedure is shown below.

Figure 20- DSC instrument with equipment's: 1-Display; 2-Specimen chamber; 3-Used pan bin; 4-Pans placement chamber; 5- Robotic pan mover.

Procedure or log method to conduct test

1. Equilibrate the sample at -10°C
2. Isothermal the sample for 1 min
3. Ramp value is 10°C⁄min to 200°C
4. Mark the end of cycle 1
5. Isothermal the sample for 1 min
6. Ramp 10°C⁄min to -10°C
7. Mark the end of cycle 2
8. Isothermal for 1 min
9. Ramp value 20°C/min to 200°C
10. Mark the end of cycle 3
11. End of method

Glass transition temperature (T_g), melting temperature (Tm) and crystallization temperature (T_c), have been recorded.

3.3.3.4 TGA

The TGA Q500 equipment was used to analyse thermal degradation of the composite samples. TGA (Thermal Gravimetric Analysis), calculates the velocity of change in difference to the mass of the sample as a function of temperature or time at a controlled atmosphere. The measurements were taken as primarily to decide the thermal stability of the composite materials.

This technique helps to determine the material loss by thermal decomposition, loss of volatiles and oxidation. It is in particular useful to study the thermal behavior of polymeric materials including fibers, films, thermoplastic, elastomers, composites, thermosets etc.

TGA measurements give valuable information that can be used to select materials for specific applications, calculate the product performance and the product quality.

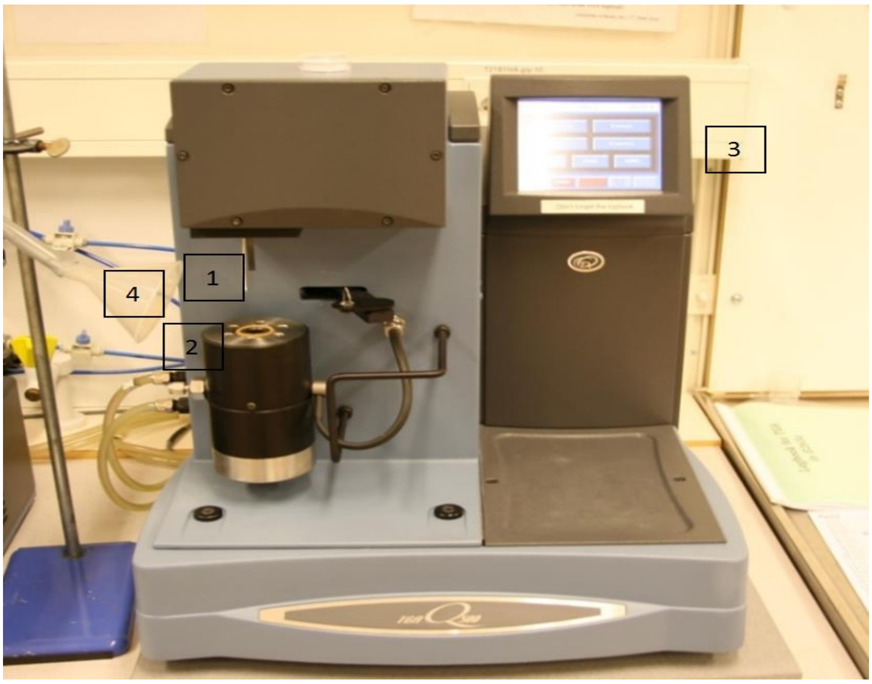


Figure 21-TGA instrument with equipment's: 1- Specimen vessel; 2- Specimen chamber; 3-Display; 4-Air passed to cool the vessel.

TGA machine was tore before loading the sample to avoid any errors. The reference composite sample (Dyneema®/Carbon Polyester/Carbon) was approximately 15-20mg and the sample was heated 10°C/min until 600°C. The inert gas nitrogen was purged inside the instrument.

4 Results and discussion

Results from the experimental work are given below in tables and figures.

4.1 Fibre tensile testing

Table 3 calculated results for tensile testing

Fibres / Properties	**Carbon**		**Dyneema®**		**Polyester**	
Gauze length mm	**25**	**70**	**25**	**70**	**25**	**70**
Elongation %	14.89±1.1	5.47±0.3	50.76±5.1	29±16.9	120± 11.1	63.09± 2.8
Initial Mod N/Tex	8.40±0.9	18.72±1.6	5.25±0.5	13.5±1.9	0.43±0.03	0.89±0.03
Linear Density Tex	66/1K tow	66/1K tow	11	11	11	11
Force at Break N	75±4.8	73.58±6.3	29±1.2	32.49± 3.3	3.99±0.2	4.07±0.4

Carbon, Dyneema® and polyester fibres were tested under standard gauze length 25mm and 70mm and the results were analysed. Carbon fibres elongation was very less and whereas the force at break was very high due its brittleness, high crystallinity, orientation of molecules. The elongation % for all fibres decreased when the gauze length was increased from 25mm to 70mm. This was due to increase in the weak points as the testing region was larger when gauze length was increased from 25mm to 70mm.

Initial modulus of the fibres increased on increasing the gauze length. The forces at break of the carbon fibres were higher than that of Dyneema® and polyester fibres. This may be because of isotropic molecules and specific precursor used during manufacturing. The other reason might be molecular orientation and C-C bonds in between carbon fibres are strong that increases the breaking force.

The polyester fibre is having high elongation percentage and low tensile strength. So it may not be applicable in the applications where tensile strength and stiffness is needed.

Fibre price performance ratio

$$Performance\ price\ ratio = \frac{Tensile\ strength(MPa)}{Price(1\ Bobbin)} \qquad \text{(Eq.6)}$$

Table 4 calculated price performance ration for fibres

Fibres price in Euros / Properties	Carbon (250€/ bobbin)		Dyneema®(150€/ bobbin)		Polyester (95€/ bobbin)	
Gauze length mm	**25**	**70**	**25**	**70**	**25**	**70**
Force at Break N/MPa	75±4.8	73.58±6.3	29±1.2	32.49±3.3	3.99±0.2	4.07±0.4
Performance price ratio	0.30 MPa/ 1Euro	0.29 MPa/ 1Euro	0.19 MPa/ 1Euro	0.21 MPa/ 1Euro	0.04 MPa/ 1Euro	0.04 MPa/ 1Euro

The performance price ratio is directly proportional to the tensile strength and inversely proportional to the cost. Table 4 shows that the carbon fibre has higher performance price ratio than the Dyneema and polyester fibres. Even though polyester fibres are cheap; it becomes expensive in terms of performance price ratio. It could be interesting to combine carbon and Dyneema fibres for it to be used as reinforcement in composites and increase the impact strength.

For example carbon fibre has 0.30MPa strength for 1Euro whereas to fulfil the same strength from polyester fibres, we need to have 0.04x8 Euro=0.32MPa.

4.2 Fabric testing

4.2.1 Microscopic test

After several trials, the final microscopic figure 15c) clarifies that the carbon fibres remain straight without any damage. Within the knitted structure; Knitting type, knitting design and several parameters influence the knitted fabric. It is possible to knit stiff carbon and flexible Dyneema fibres.

During industrial use it is compulsory to test in Scanning Electron Microscope (SEM) to check each individual filament breakage. A small breakage in the fibres can cause a severe damage in the composite and directly effect on its properties.

4.3 Composite materials

4.3.1 Tensile testing:

Table 5 calculated tensile strength results for composite materials

Fibres / Properties	Dyneema®/Carbon		Polyester/Carbon	
Specimen	1a (0°)	1b (0°/90°)	2a (0°)	2b (0°/90°)
Tensile strength MPa	384 ±17	95.39 ±15	364 ±16	**34.68 ±6**
Modulus GPa	95.73 ±17	25.75 ±5	79.40 ±3.9	4.75 ±0.5
Elongation %	0.429	0.588	0.392	0.26
Breaking strength	384 ±17	95.3 ±15	364 ±16	**16 ±3**

In carbon composites, it is common that the matrix fails before carbon reinforcement on loading. It is very rare to break both carbon and resin at the same time.

The tensile strength and breaking strength of composite 1a and 2a was higher than that of the composites 1b and 2b. Four layers of carbon reinforcment was placed in the same direction (0°) in the composite 1a, 2a and the tests were performed along machine direction; whereas in 1b and 2b, two layers are placed in 0° and 90°.

The elongation% of 1a and 1b is higher than that of 2a and 2b. This was due to interensic properties of Dyneema and polyester fibres. In the fibre tensile testing the elongation% of Polyester was little higher compared to Dyneema but in the composite it is reverse.

The modulus of 1a and 2a is higher than that of 1b and 2b. The modulus of 2b was very low and this could be due to the detection of polyester breakage by the software; whereas the modulus of 1b was influenced by Dyneema fibres. This might be due to carbon fibers taking force and other fibres are not taking any force, they are just elongating. This is because Dyneema and polyester having high elongation% than the carbon fibres. Another reason might be orientation of fabric layers is different in 0° and 0°/90°.

This shows that the tensile properties of composite is directly depend on the resin content in composite, carbon fibre orientation, wales/inch and course/inch of the knitted fabric.

Composite price performance ratio

$$Performance\ price\ ratio = \frac{Tensile\ strength(MPa)}{Price(1\ Bobbin)} \qquad \text{(Eq.7)}$$

Table 6 calculated price performance ration for composite

Fibres / Properties	Dyneema®/Carbon (400 Euro)		Polyester/Carbon (245 Euro)	
Specimen	1a (0°)	1b (0°/90°)	2a (0°)	2b (0°/90°)
Tensile strength MPa	384 ±17	95.39 ±15	364 ±16	34.68 ±6
Performance price ratio	0.96 MPa/ **1Euro**	0.23 MPa/ **1Euro**	0.91 MPa/ **1Euro**	0.14 MPa/ **1Euro**

The composite price performance ratio was calculated when the reinforcement was combination of 2 fibres that was reinforced in epoxy matrix and it is different from the fibres price performance ratio. The 1a and 2a are almost similar as shown in the table 6, and can be used in those applications where unidirectional tensile strength is needed. This concludes that polyester may be used in replace of Dyneema® fibres in terms of proportional ratio. In some cases we have to consider the elongation and the modulus.

4.3.2 Impact testing:

Table 7 calculated results of composite strips for impact resistance

Specimen / Properties	1a (0° or DC 1)	1b (0°/90° or DC2)	2a (0° or PC 1)	2b (0°/90° or PC 2)
E (J)	0.6969 ±0.2	0.4255 ±0.05	0.6211 ±0.009	0.6178 ±0.06
E/W (J/mm)	0.2409 ±0.3	0.3799 ±0.04	0.7058 ±0.01	0.6759 ±0.05
E/A(KJ/m^2)	70.8324 ±8.0	38.3715 ±4.6	72.7633 ±1.1	67.9285 ±5.2
E/A(J/m^2)	0.0708 ±0.0	0.0383 ±0.004	0.0728 ±0.001	0.0680 ±0.005

Table 7 shows that 1a and 2a composites absorb same amount of energy; while 1b absorbs lower energy compared to 2b. This may be, 1b is having less modulus compared to other specimen during composite tensile testing. Lower impact strength of 1b than 2b could be due to higher modulus of 1b composite. This was due to Dyneema fibres, whereas 2b has low modulus polyethylene fibres that influence impact properties.

Table 3 shows that the polyester fibres have elongation up to 120% and it may be the reason to have high impact resistance in composites 2b and less in 1b.

4.3.3 DMTA

The tests were done at several frequencies via sinusoidal force and thus have more data on the graph. The frequency range was from 1-100 Hz, after careful observation the highest frequencies were selected i.e., 100Hz and other frequency curves were diminished in the graph. The main idea was to visualize the damping properties of the carbon composites. So, loss factor and storage modulus are noted at 100Hz for Dyneema®/carbon and polyester/carbon specimen. Usually in all DMTA, the loss factor is designated as tan delta.

Dyneema®/ Carbon

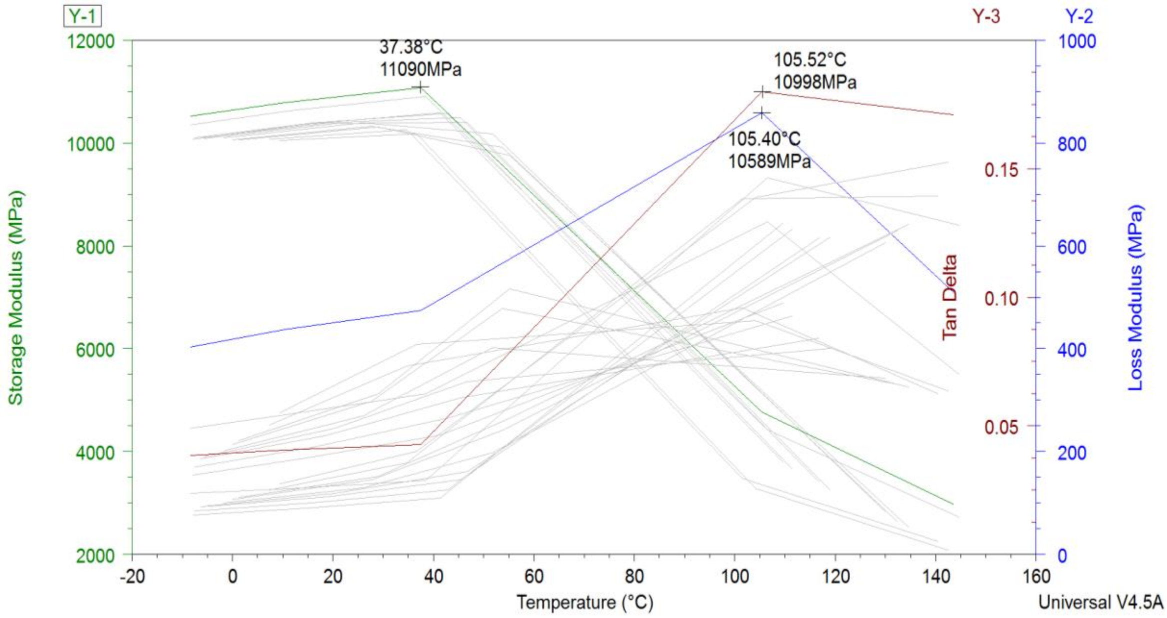


Figure 22 Representative of stress strain starts at 37.38°C

Polyester/ Carbon

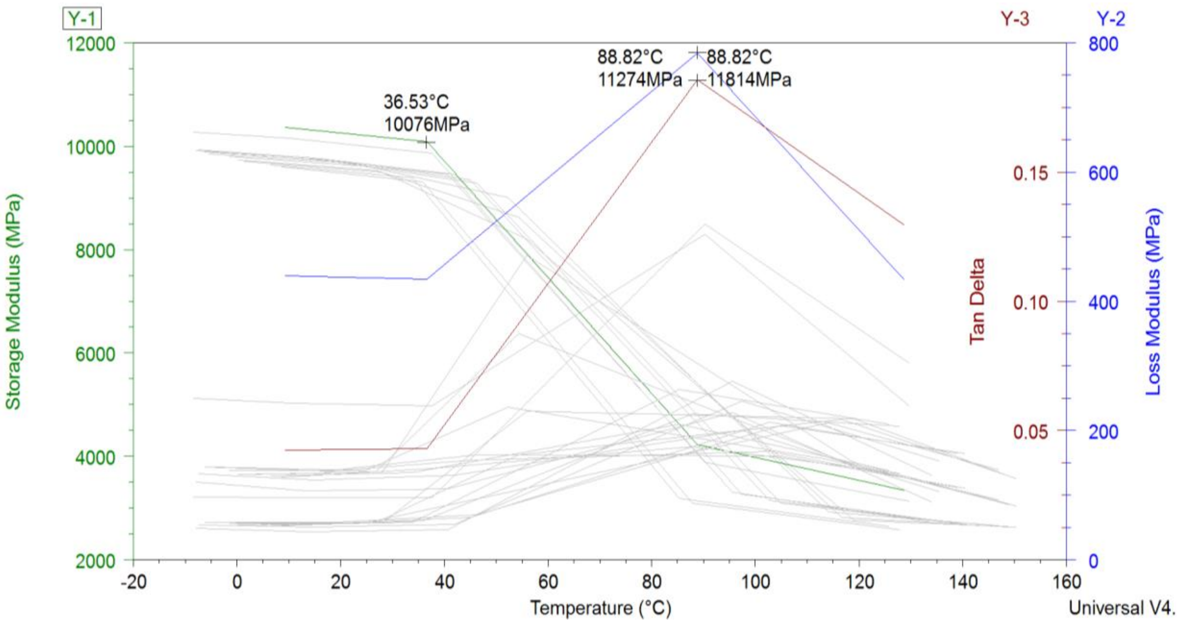


Figure 23 Representative of stress strain starts at 36.53°C

Table 8 Identified storage and loss modulus for composite materials from below figures

	Dyneema®/Carbon	Polyester/Carbon
Storage modulus E1	11.09GPa	10.07GPa
Loss modulus	860MPa	780MPa
Tanδ	0.175	0.185

From the figure 22, we can conclude that storage modulus is at 37˚C and then loss modulus will also be at 37˚C. Due to stiffness of the carbon fibres the loss modulus is reached up to 11GPa at 105˚C. The other reason may be due to the high elongation percentage of the Dyneema fibres withstands the stress at higher frequency.

In figure 23, storage modulus is at 36˚C and then loss modulus will also starts at 36˚C. Due to stiffness of the carbon fibres the loss modulus is reached up to 11GPa as similar to Dyneema/carbon composite but at 89˚C. The other reason may be due to the high elongation percentage of the polyester fibres and low tensile strength. As the graph clarifies that there is a more difference from 100Hz frequency to other frequency rates.

The stress and strain ramp from figure 22 and 23 shows similar results for storage modulus. This may be due to the high epoxy content in the composites.

4.3.4 DSC

This technique was used to calculate the Tg, glass transition temperature for 2 different kind of composites.

Dyneema®/ Carbon

The Dyneema®, carbon and epoxy in the composite changes its thermal properties on changing temperature as shown in the figure 24. The glass transition temperature was about 50°C, where the phase change occurs i.e., rubbery to glassy state. The content of the crystalline phase of melting is at 155°C for the Dyneema fibers. Here, there are movements in the chains.

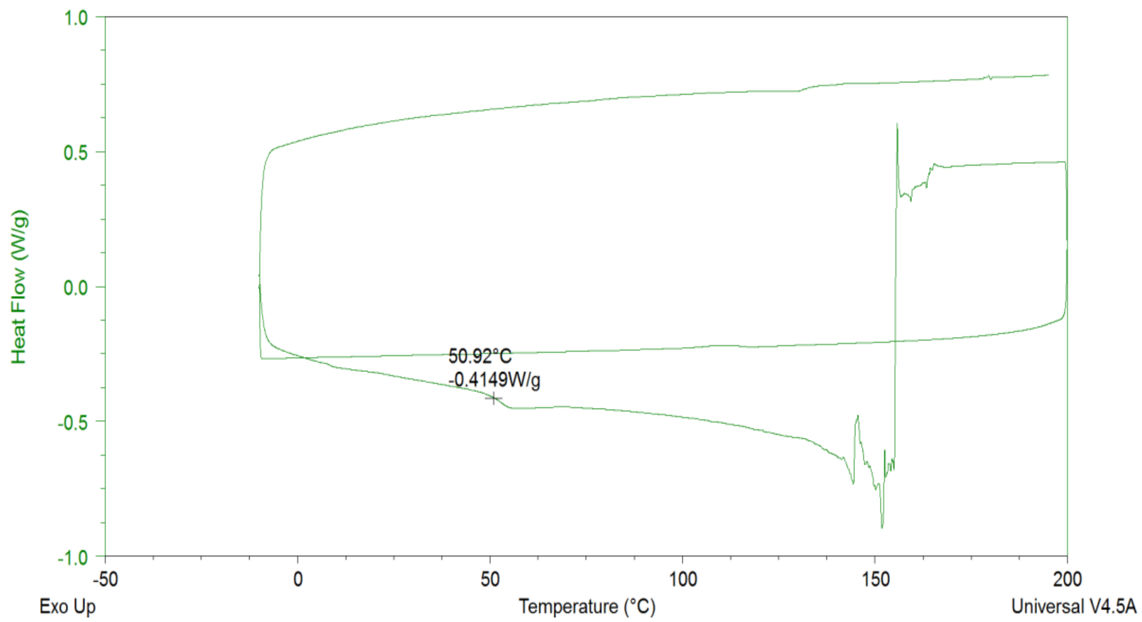


Figure 24 Representative of a drop in Tg at 50.92°C and further Dyneema melts around 145°C

Polyester/ Carbon

The polyester, carbon and epoxy in the composite change its thermal properties on changing temperature as shown in the figure 25. The glass transition temperature was about 50°C, where the phase change occurs i.e., rubbery to glassy state. Here, there are movements in the chains. The content of the crystalline phase of melting is at 110°C for the polyester fibers.

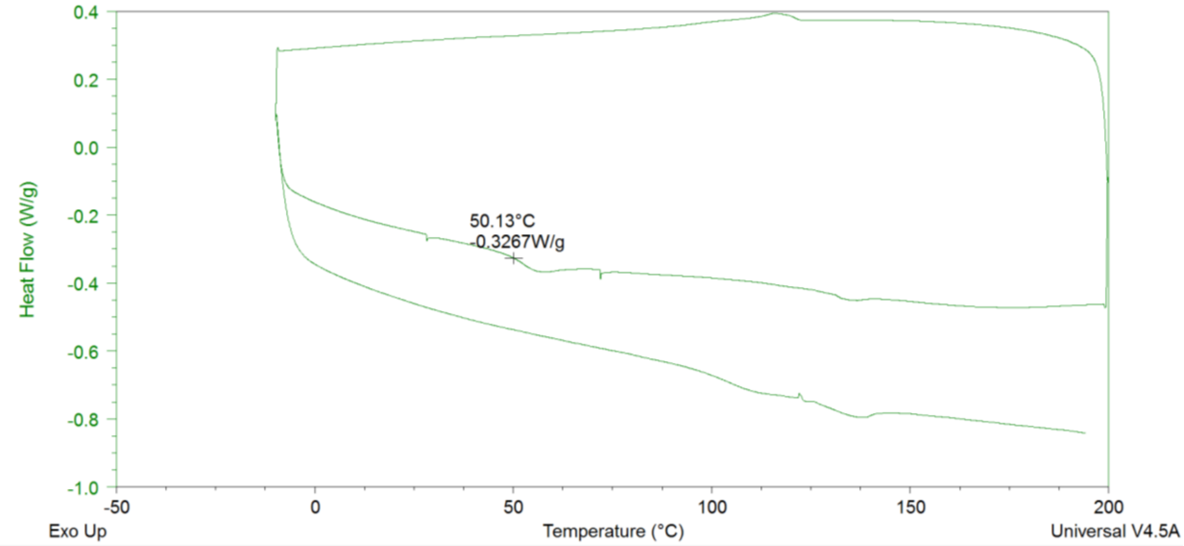


Figure 25 Representative of a drop in Tg at 50.13°C and further polyester melts around 120°C

In the both DSC curve, I can observe Tg at ±50°C, this might be due to the high percentage of epoxy in the sample. The degradation of sample takes in the amorphous state and rearrange of crystallization occurs at 50°C.

4.3.5 TGA

Dyneema®/ Carbon

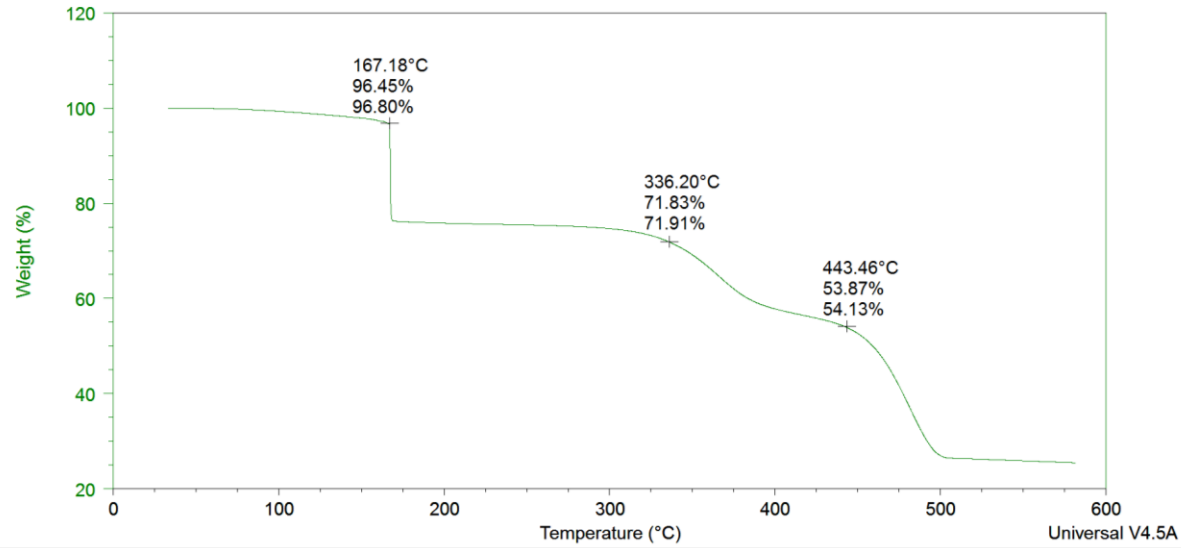


Figure 26 Representative of a drop in Tg at 167°C and later in two stages at 336°C and 443°C

TGA was used to study the thermal stability of the composites. The Dyneema®/ Carbon specimen was decomposed in three stages. The result from the figure 26 shows that at 167°C the first degradation starts. Further the mass loss starts in two steps concludes that it is degrading at 2 stages. This might be maximum degradation occurs at maximum temperature and minimum degradation at minimum temperature. Then polymer material remains as it is because it withstands high temperature. The other reason may be highest percentage of polymer content in the composite.

Polyester/ Carbon

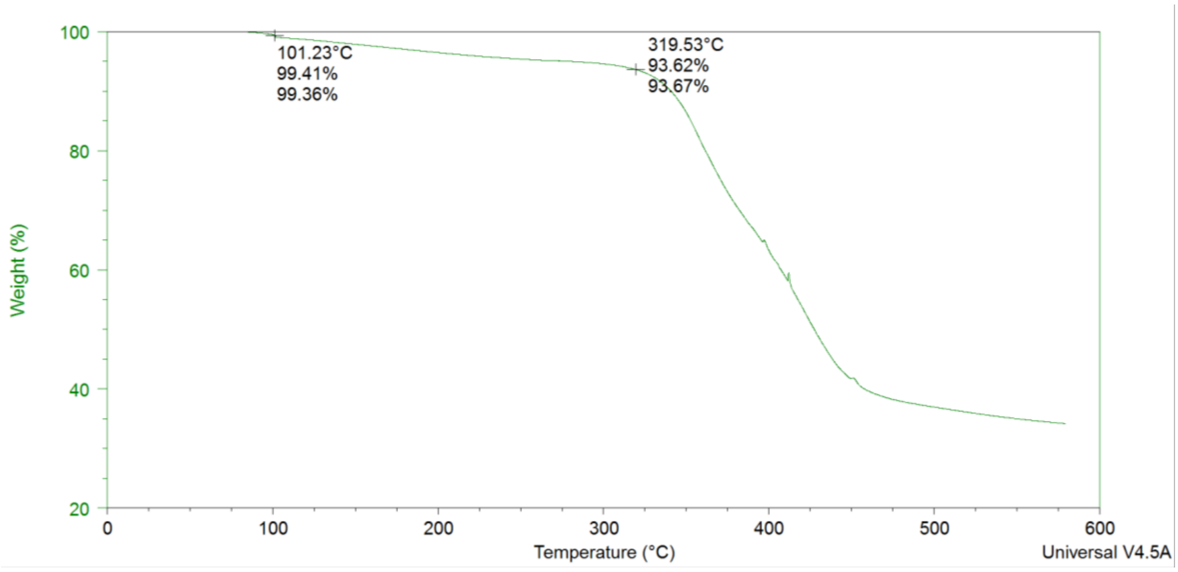


Figure 27- Representative of a drop in Tg at 101°C and 319°C

The temperature drop at 101°C is may be due to the moisture content in the material. The Polyester/carbon composite is decomposed at 319°C. This is lower than that of Dyneema/carbon composite and this may be due to the polyester content. In both the composite specimen the polymer reaches to high thermal condition this may be due to the more crosslinking of chains.

4.4 Environmental safety, sustainability and its advantages for society

Humanity is facing severe environmental problems due to improper disposal of inorganic materials. Similarly, composite usage could cause sustainability issues as composite recycling is a challenging task. However, there are methods to recycle composites but the recycling process has to be optimized.

A pyrolysis method; is a thermal degradation process used to separate the carbon fibres and resin content. The separated material is recycled and reused to manufacture new composite parts. Energy can be extracted from the organic resources.

The other method is mechanical recycling; grinding the composite parts and used as a whiskers or reinforcement in the new composite.

One should consider the life cycle analysis, when it comes to evaluating sustainability. Automotive industries are keen in reducing the weight of the car in order to increase the fuel efficiency and therefore reduce the environmental impact. The products like heavy metal parts used in automobiles consume more fuel and release more carbon di oxide (Soraia Pimenta, 2010).

In recent years composite materials are replacing heavy metal parts in automotive application and carbon composite manufacturing is increasing rapidly. These composites are lighter in weight and consume less fuel, and thereby reducing the impact on the environment (Krishan Chawla, 2012).

Hence in this thesis inclusion of Dyneema fibres makes the carbon composite more light and increases the fuel efficiency of vehicles. The composite from the end of life vehicles should be recycled either by pyrolysis, where energy is recovered from organic materials and the carbon fibres can be recovered, or by mechanical recycling where the grinded composite materials can be used as filler in the new composites (Pierfrancesco Cerruti, 2014).

The recycled carbon composite parts have lower mechanical properties and variation in stress-strain behaviour of whiskers due to discontinuous fibres after grinding. Hence they are used in less critical applications such as cabin hood in automobile industry (Krishan Chawla, 2012).

The process of preparing has also impact on environment. One should consider the amount of energy used to manufacture the product, the time of manufacturing and the waste produced during the manufacturing. Earlier the reinforcement was manufactured using weaving, braiding and other methods which it was limited to flat composite parts.

In this thesis the knitting technology can give the better drapabiity and stretch ability to use for curved shape composites. This reduces the waste and also makes it easy to manufacture small parts.

Optimizing the recycling process and good manufacturing process of carbon/Dyneema and carbon/polyester composites will not only reduce the negative impact on environment, it will also reduce the cost of the composite.

5 Applications of knitted preforms for composite applications

a. The composite material made of braiding and weaving used as a reinforcement material was compared with the composite material made from knitting.
   Both braiding and weaving have good torsional stiffness, bending stiffness.
   They are used in beams and load carrying structures

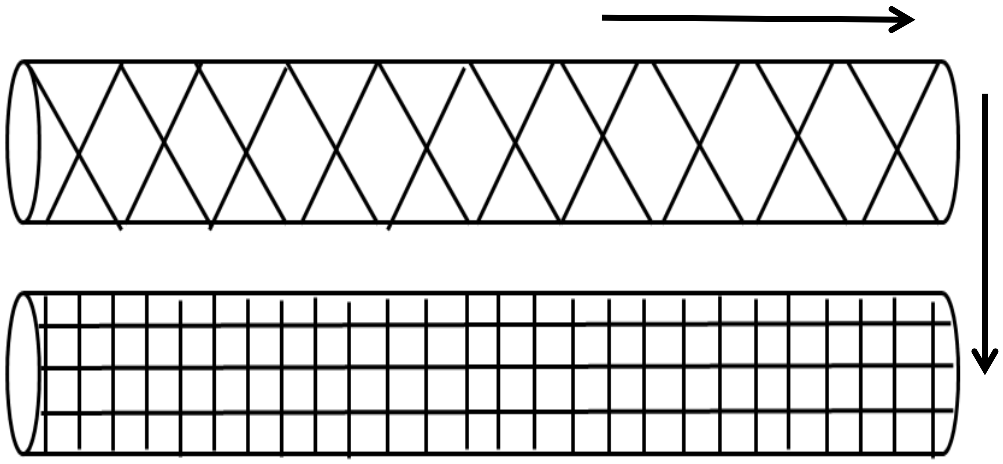


Figure 27- Braiding and weaving has good bending and torsional stiffness

b. The composite material made of circular weft knitting as a reinforcement material
   Circular weft knitting has no torsional stiffness
   Circular weft knitting has no bending stiffness
   Circular weft knitting has large expanding stiffness as shown in the figure 28.
   They are used in rocket nozzles and liquid natural gas outer body.

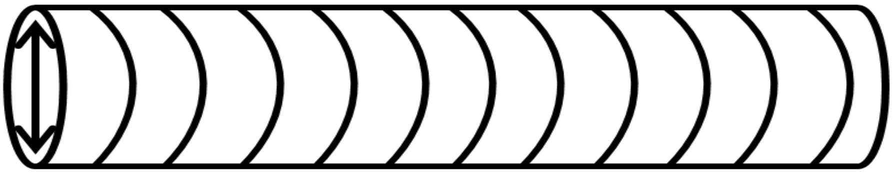


Figure 28- Circular weft knitting has large expanding stiffness due to its extensibility

6 Conclusion

The stiff carbon fiber and flexible fibers like Dyneema and polyester; was knitted in a circular weft knitting machine. The fibers were knitted however without the carbon fiber breakage and some of the properties achieved like good dimensional stability, extensibility, easy handling. This is due to the fact that the knitted fabric could be used in the 3D composites which fit for contour shapes. This might also saves the production time, cost and used in several applications.

I could clearly feel that the knitted fabric drape ability was good, stretchable and good handling properties.

The experimental result shows that the carbon fibers percentage should be high in the composite to withstand the properties. Blending of Dyneema and polyester fibres will not affect that much in unidirectional orientation of fabrics during composite preparation.

The results from the DMA, TGA and DSC experiment we conclude that the Tg is lowered because of high fiber volume fraction of Dyneema and polyester fibers.

An increase in the temperature and moisture content; results in faster degradation of the composite material and directly effects on the properties. The thickness of the composite material is also taken under consideration.

The final conclusion is that change in knitting structures, loop length and design in knitted fabric can be used for more complex shapes to make a composite.

7 Future experimental research method

1. Due to limited resources and time in this project, I was unable to knit those yarns in warp knitting and conduct tests. But it gives the clear net shape preform and can be considered for the future work to compare with these results. The reinforcement or the alignment of carbon fibres in the 2 direction makes the fabric to withstand load in 2 directions and have very drape ability to fit for contour shapes.

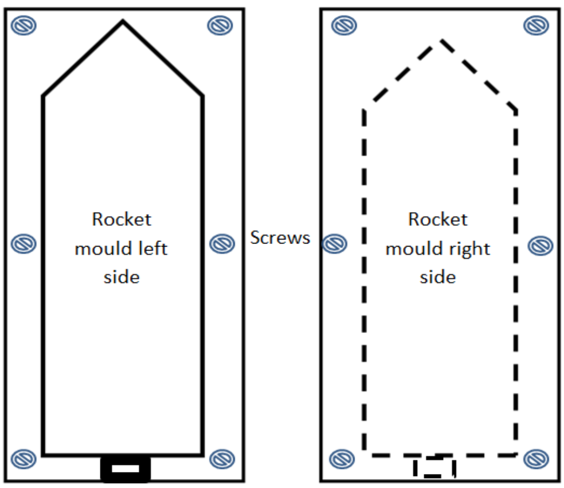
2. Drape ability test is conducted for the different tow size of carbon fibres.

3. Explanation is given below that how could this idea to be worked and expanded.

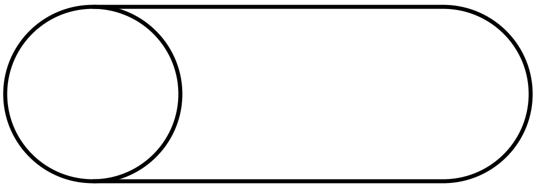
In my work the knitted carbon and Dyneema® fabrics were used as a reinforcement material in the composite manufacturing. These composites are tested for several tests and results are put forward. This idea will help in making the applications like rocket nozzles and liquid natural gas tankers. The rocket nozzle burns the fuel at high temperature and pressure to escape from the gravity point. In the liquid natural gas, the high pressure of gas is compressed in a gaseous state i.e., 2.4 times higher to make easy for the transportation. In both of these applications the pressure will be built from inside out and they are using heavy metal container which is heavy weight, fuel consuming matter in transportation.

First the 3D design is done in CAD to make a mould and tested as per needed

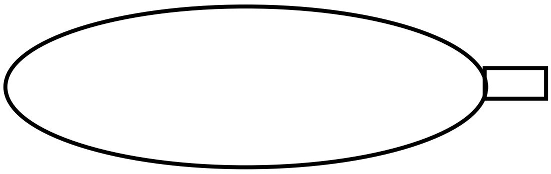
Then the left and right mould is prepared in the shape of rocket or gas container.



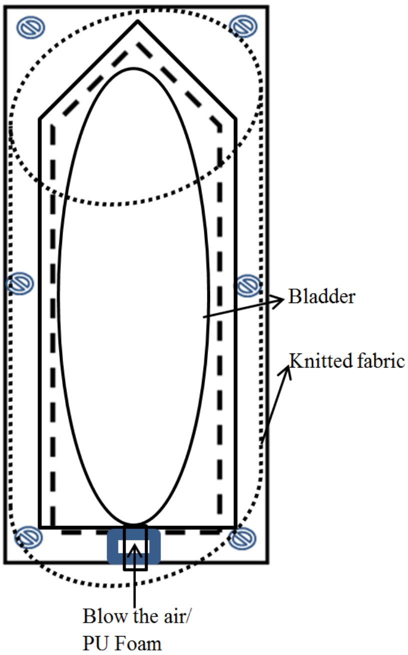
- The circular weft knitted fabric using carbon fibers and Dyneema® fibers is taken to ply in between the moulds. The fabric height and width should be little more extra than the mould.



- The bladder or balloon is taken and placed inside the circular weft knitting.



- Then bladder is placed inside the circular knitted fabric and dips it in a resin bath. The resin impregnated fabric along with bladder is placed according to shape in between the moulds and tight the screws.



- Once the mould screw is tightened, foam is passed along with water to expand the bladder and get the shape of the mould. The mould is heated at suitable temperature for easy curing.
- Higher the carbon tow size high expanding properties achieved at the end and could be used in bigger liquid natural gas containers.
- Could be explored more and need to do more test to find its application in other areas.

Bibliography

A R Horrocks and S C Anand, (2000). *Handbook of technical textiles.* Cambridge, England: Woodhead publishing limited .

Antonio Miravete (1999). *3D textile reinforcments in composite materials.* University of Zaragoza, Spain: Woodhead Publishing Ltd and CRC Press LLC.

Bagherpour and Salar. (2012). Fibre Reinforced Polyester Composites. INTECh, pp.135-166.

C. A. Lin, (2008). Manufacture of polyester fibres. *Polyester and polyamides*, Woodhead publishing limited, pp. 62-76.

Carmaine Mozza and Paola Zonda (2001). The knitwear handbook. *ACIMIT Foundation*, pp. 60-70.

Christian Heiss, Nahum Travitzky and Peter Greil, (2012). Manufacturing of Silicon Carbide Knit Fabrics. *Advanced engineering materials,* pp 162-165.

Congswell, F. N. (1992). *Thermoplastic aromatic polymer composites.* Melksham, Wiltshire: Butterworth-Heinemann ltd.

Dorin Ionesi, Ramona Ciobanu, Mirela Blaga and Costea Budulan (2010). Knitted Preforms For Composites Materials. *7th International Conference*.

F.C.Cambell. (2010). *Structural composite materials.* ASM International.

Güneri Akovali,(2001). Handbook of Composite Fabrication. Shawbury, UK: Rapra Technology Limited.pp. 103-115

J. G. H. Bouwmeester, R. Marissen and O. K. Bergsma (2008). Carbon/Dyneema® Intralaminar Hybrids:New Stratergy To Increase Impact Resistance Or Decrease Mass Of Carbon Fibre Composite. *26th International Congress Of The Aeronautical Sciences.*

J.P.Attwooda, S. K. (2014). The out-of-plane compressive response of Dyneema® composites. *Journal of the Mechanics and Physics of Solids*, pp. 200-226.

Jorg Mayer, Joop De Haan, Roland Reber And Erich Wintermantel (1999). Knitted Carbon Fiber Reinforced Thermoplastics, Structure- Properties relation. *Materials Science Research International*, pp. 143-150..

Kimiyoshi Naitoa, Yoshihisa Tanakaa, Jenn-Ming Yangb and Yutaka Kagawac (2008). *Tensile properties of ultrahigh strength PAN-based, ultrahigh modulus pitch-based and high ductility pitch-based carbon fibers.* Japan: International journal.

Krishan Chawla, (2012). *Composite materials.* Birmingham, USA: Springer New York Heidelberg Dordrecht, pp 214-298.

Amnon Katz and Victoe C Li (1995). Inclination angle effect of carbon fibres in cementitious composites. *Journal of engineering mechanics*.

Liu, Y. Q. (2015). Bending Properties of the Multilayer-Connected Biaxial Weft Knitted Fabrics-Reinforced Composites Made with Carbon Fibers. *Polymer composites*.

Mădălina Zănoagă And Fulga Tanasă (2014). Complex Textile Structures As Reinforcement For Advanced Composite Materials. *"Petru Poni" Institute of Macromolecular Chemistry of Romanian Academy, Iaşi*. Romania.

Marian L Gaucherand And Martin W. King, (1983). Predicting the Drape Coefficient of Knitted Fabrics. *Textile research journal*, pp. 293-303.

Murali Krishna Yantrapati and Narendra Kumar Jinka, (2015). Fabrication and Performance of Fiber Reinforced Composite Material by Using Sunhemp Natural Fiber. *International Journal of Emerging Technologies in Engineering Research (IJETER)*, pp.11-17.

O.Diestel, P.offermann and H.Cebulla, (2002). Fully fashioned biaxial weft knitted fabric. *AUTEX research journal*, pp 8.

Park and Soo Jin. (2015). *Carbon fibres.* South Korea: Springer Series in Materials Science.

Pierfrancesco Cerruti, Filippo Fedi, R.A., Gennaro Gentile, C.C., Paola Persico, M.E.E., Mario Malinconico and Maurizio Avella (2014). Up-Cycling End-of-Use Materials: Highly FilledThermo plastic Composites Obtained by Loading Waste Carbon Fiber Composite into Fluidified Recycled Polystyrene. *Polymer composites*, 1621-1623.

R Alagiruswamy, Naveen V Padaki and B S Sugun (April 2006). Knitted performs for composite applications. *Journal of Industrial textiles*, pp. 295-305.

Sadhan Chandra Ray (2011). *Fundamentals and advances in knitting technology*. New Delhi, India: Woodhead Publishing India Pvt. Ltd.

Sandip Mukherjee, Sadhan Chandra Ray and S K Punj (2014). Dimensional parameter of 1X1 Rib fabric produced on a circular bed double jersey knitting machines using ultrasonic technique. *Indian Journal of fibre and Textile Research*, pp.230-237.

Soler Miquel (2014). Textile structure for Aeronotics. *Centre de Recerca i Transferència de Tecnologia Tèxtil de Canet de Mar*, pp.107-112.

Soraia Pimenta and Silvestre T. Pinho. (2010). Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. *The Composites Centre, Department of Aeronautics*, 378–392.

Tianmei Zhong and Hong Hu, (2007). Formability Of Weft-Knitted Fabrics On A Hemisphere. *AUTEX Research Journal*, pp. 245-251.

Xiaogang Chen, Y. Liu, (2015). Three-dimensional knitted textiles. In X. Chen, *Advances in 3D Textiles* China: A volume in Woodhead Publishing Series in Textiles, pp. 125-152

Xiaoping Ruan & Tsu-Wei Chou, (1996). Experimental and theoretical studies of the elastic behaviour of knitted fabric composite. *Composite science and technology*, pp. 1391-1403.

Xiaosong Huang, (2009). Fabrication and Properties of Carbon Fibers. Chemical Sciences & Materials Systems Laboratory, General Motors Research & Development, pp. 2369-2403.

Yexiong Qi, Jialu Li and Liangsen Liu, (2015). Bending Properties of the Multilayer-Connected Biaxial Weft Knitted Fabrics-Reinforced Composites Made With Carbon Fibers. *Polymer Composites*, pp. 2291-2302.