Study of the Curing Process of CFRP by Means of Electricity

Heating of the Carbon Fiber Reinforced Polymer (CFRP) during the curing process by conducting electricity through the fibers (Baltic Yachts)

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Abstract

This thesis is part of my double degree studies on Energy and Environmental Engineering by Novia University of Applied Sciences, from Vaasa, Finland, and Mechanical Engineering by the University of Lleida, from Lleida, Spain.

This study was requested by the company Baltic Yachts in order to determine the possibility to increase the efficiency of the process of heating carbon fiber pieces. This process referred to as curing, is part of the treatment of Carbon Fiber Reinforced Polymer (CFRP) structures to achieve the desired physical properties. CFRP is a composite material with superb properties. The manufacturing of CFRP has high needs of energy, and thus it becomes expensive.

The company Baltic Yachts is a company in the sector of designing and building exclusive sailing yachts made of CFRP. This is cured and molded in the company with heat treatments up to 115°C.

The objective of this project is to determine the suitability of heating the CFRP by means of conducting electricity through the carbon fibers. The report consists of a theoretical part, lying in a research of information, and a second part, lying in different experimental tests to study the behavior of carbon fiber while conducting electricity.

Language: English

Key words: carbon, fiber, reinforced, polymer, curing, molding, environmental, mechanical

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PART 1: INTRODUCTION AND OBJECTIVE

1. Introduction

Engineering materials may be classified into different types: metals and alloys, ceramics and glasses, polymers, semiconductors, and composite materials. The composite materials consist of two or more materials with dissimilar properties in order to form a new material with enhanced properties.

Carbon fiber reinforced polymer (CFRP) is a composite material with superb properties. The use of CFRP is continuously increasing in a number of applications such as aircrafts, space shuttles and satellites, automobiles, marine sector, infrastructures, sport goods, and even biomedical applications. It is though among the most expensive to produce due to high needs for energy and time, thus it is mainly used in high-performance applications.

CFRP has high tensile and compressive strength, high module outstanding fatigue life, no corrosion, and light weight. The manufacturing process includes the manufacturing of the carbon fibers and the curing and molding of the polymer. In both processes, heat treatments with large needs for energy are applied.

Baltic Yachts is a company that designs and builds high-tech, high-performance sailing yachts made of CFRP. The process of manufacturing the carbon fibers do not take place at the company; however, the curing and molding of the CFRP is performed there. This process implies heat treatments to up to 115°C. At the moment the heat treatment is performed in two stages, one up to 80-90°C, and the other up to 115°C. The first step is performed in a wooden oven that looks like a sauna. The raw CFRP is mounted on molds and heated up. The second step is performed by applying electric blankets on the resulting CFRP from the first step.

2. Objective

Increasing the efficiency of the manufacturing processes and the efficiency throughout the lifespan of the products has become a major issue in most companies. This fact may be approached both from an environmental point of view and from an economical point of view. To improve the efficiency of the processes means to reduce the amount of energy needed to perform a certain task. This decrease in the consumption of energy obviously brings a reduction of the costs but, in addition, it also implies lower environmental impact.

The company Baltic Yachts has been using lightweight sandwich constructions since the 1970s. Today, the company has a large trajectory in using CFRP since they have been using it for more than 25 years. Nowadays, the company intends to lower the consumption of time and energy especially during the curing and molding processes. Therefore, an option is to perform the heat treatments using another method.

The objective of this project is to determine the suitability of heating the CFRP by means of conducting electricity through the carbon fibers. The development of this report consists of two main parts. The one part is theoretical and mainly lies in a research of information in order to have a broad knowledge on the CFRP, and more in detail on the manufacturing process and properties. The other part is experimental and includes different tests that have been carried out in the laboratory in order to study the behavior of carbon fibers while conducting electricity. In this part different samples provided by the company are to be used.

PART 2: THEORY

3. Composite materials

Composite materials are formed from the combination of two or more materials with dissimilar properties in order to form new materials with enhanced properties. This type of materials is distinguished by notably achieving better –useful or structural- properties than those of the components themselves. The microstructure of composite materials is non-uniform, discontinuous and multiphase due to the combination of the different materials, giving those characteristics that cannot be found neither in metals, ceramics, nor polymeric materials.

The classification of composites as a type of materials started in the second half of the 20^{th}, and during the last four decades these have been the prevailing developing materials. Applications of composites can be found in the high-tech products of the aerospace, underwater, bioengineering, and transportation sector. Nowadays, composite materials are also referred simply as composites.

3.1. History

The oldest and most important composite materials are those that can be found in the nature, and so known as natural composites. The most common composite of this type is wood, which consists of a reinforcement of cellulose fibers and a lignin matrix. Cellulose is a strong and flexible material and lignin endows stiffness to the composite.

Non-natural composites have been used since the prehistory. The first man-made composite to be used is bricks made of straw and mud. Concrete –and reinforced concrete- and asphalt are also examples of composite materials that have been widely used since the beginning of the 19^{th} century. In the present, the composite materials engineering tends to focus on the development of new artificially made composites.

3.2. Components of composite materials

The constituent materials in the composites remain recognizable and keep their physical, chemical and mechanical characteristics, in opposition to what happens in metal alloys. The constituent materials must be insoluble in each other, physically dissimilar and chemically inhomogeneous.

Composites can be made of two or more constituents; the simpler and most common composites are those that only consist of two different components. The two constituents are the matrix or continuous phase and the reinforcement or dispersed form. The matrix is a continuous phase in which the reinforcement is embedded; thus, the matrix surrounds the reinforcing phase, as shown in Figure 1.

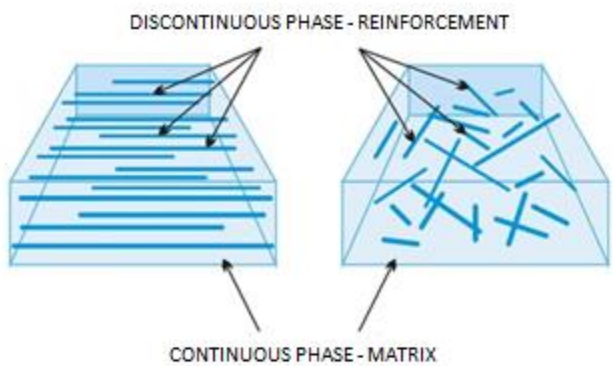

Figure 1. Schematic representation of the structure of a composite[1]

Reinforced concrete is a composite material that is widely used in the building sector. As such, it consists of a matrix and a reinforcement. In this case, both components can be easily distinguished. The matrix or continuous phase is concrete and the reinforcement or dispersed phase is steel bars. The reason of using these two materials together is that

[1] http://www.essentialchemicalindustry.org/materials-and-applications/composites.html

concrete has a high strength to compression loads but does not resist well tension loads whereas steel withstands much better tension loads than compression loads otherwise.

Figure 2. Photograph of the building of a structure made of reinforced concrete[2]

3.3. Reinforcement

The reinforcement or dispersed phase usually provides the strength and stiffness. There are different types of reinforcements: whiskers, particles, and fibers, being the most common fibers and particles.

Particulates have dimensions that are approximately equal in all the directions. Particulate composites are much weaker and less stiff than fiber composites; nonetheless, their main advantage is the reduced cost. They are more brittle and difficult to process. The orientation of the particles is not significant and they are regularly used as fillers to reduce the cost of the materials.

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[2] http://www.ulmaconstruction.com.ar/

Whiskers are single crystals which are very small in both length and diameter with regard to the size of the fibers. These have an exceptional strength but are hard to spread in the matrix.

Fibers are distinguished by having a small section compared to their length; that is to say, their length is much larger than their diameter. These are usually produced by drawing or pulling and, therefore, they have a higher strength in the long direction. The ratio between the length and the diameter is defined as *aspect ratio*. Dependent on this ration, fibers can be sorted into continuous fibers and discontinuous fibers. Continuous fibers have a large aspect ratio; on the contrary, discontinuous fibers have a small aspect ratio. Continuous fibers usually have a particular orientation while discontinuous fibers normally have a random orientation. Continuous-fiber composites are manufactured in laminates by piling sheets of continuous fibers in different orientations. The different types of reinforcements can be observed in Figure 3.

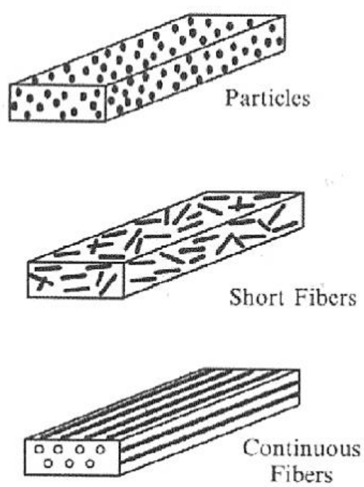

Figure 3. Schematic representation of the different types of reinforcements in composites[3]

[3] http://kansu.tripod.com/me451/2.html

The most common type of composites is the fiber-reinforced. These offer higher strength and stiffness due to the small diameter of the fibers. The reducing of the diameter implies fewer defects, and thus higher strength; however, it also implies a higher cost. In addition, a small diameter also brings more flexibility.

The most common fibers are glass, aramid, and carbon. The maximum volume of the fibers in the composite is around 70%; with larger rates there is too little matrix to bind the fibers effectively.

Theoretically, the strength of discontinuous-fibers composites can be as high as that of continuous-fiber composites, if the fibers were aligned and had a high aspect ratio. Nonetheless, this is an assumption that is very difficult to achieve. Therefore, discontinuous fibers are usually non-aligned, and thus the strength and modulus of discontinuous-fiber composites is substantially reduced. Hence, continuous-fiber composites are used where high stiffness and strength are required, implying a larger cost; while discontinuous-fiber composites are used where the cost is the principal factor taken into account.

3.4. Matrix

The main functions of the matrix phase are to maintain the fibers together and in the proper orientation and to protect them from mechanical abrasion, chemical reactions, and effects from the environment. This can be a metal, polymer, or ceramic. The choice of the material is usually based on the desired ductility and the range of temperatures that it will have to face during its use.

In metal-matrix composites and polymer-matrix composites a strong bond is formed between the fibers and the matrix. In this case, the matrix provides a medium through which externally applied loads are transmitted and distributed to the fibers, and it stops crack propagation among them by keeping them separated. Furthermore, the matrix also provides certain ductility. In ceramic-matrix composites, the goal is to improve the brittleness since ceramics are already stiff and strong.

The metal-matrix and ceramic-matrix composites have been less developed than polymer-matrix composites since the production processes are more complex. These require higher temperatures and pressures than the polymer-matrix composites, and thus have higher costs.

The materials that are the most widely used as matrix are polymers, which can be thermoplastics and thermosets. Thermoplastics are produced from a resin with high viscosity that is processed by heating it above its melting point. Thermosets are produced from a resin with low viscosity that reacts and cures during the processing, and forms an intractable resin.

Thermosets are more used than thermoplastic because they usually have a better heat resistance. Among this, epoxy is the most common. The most commonly used polymer-matrix composites are Glass Fiber-Reinforced Polymer composite (GFRP), Carbon Fiber-Reinforced Polymer composite (CFRP), and Aramid Fiber-Reinforced Polymer composite (AFRP).

3.5. Unidirectional and quasi-isotropic composites

Materials can be grouped into either isotropic or anisotropic. Isotropic materials are those that have the same properties in all the directions; therefore, normal loads only produce strains in the same direction. On the other side, anisotropic materials are those that have different properties in all the directions; there are no planes of symmetry and normal loads do not only produce strains in the normal strains but also shear strains.

Metals and polymers are usually classified as isotropic materials while composite materials are classified as anisotropic materials. Composites are also classed as orthotropic materials. These are a subtype of anisotropic materials whose properties differ in the three orthogonal directions.

The manufacturing structure of composite materials is based on the desired isotropy. Notwithstanding, composites are manufactured into layers or plies. These layers can be piled in the same orientation forming a single ply or lay-up known as *lamina* or *unidirectional lay-up*. If these layers are piled in different orientations, they form a single ply or lay-up known as *laminate* or *quasi-isotropic lay-up*.

Continuous-fiber composites are usually laminated materials where the layers are made up in different orientations so as to improve the strength in the primary loads direction. Unidirectional lay-ups are obviously very strong and stiff in only one direction while very weak in the others.

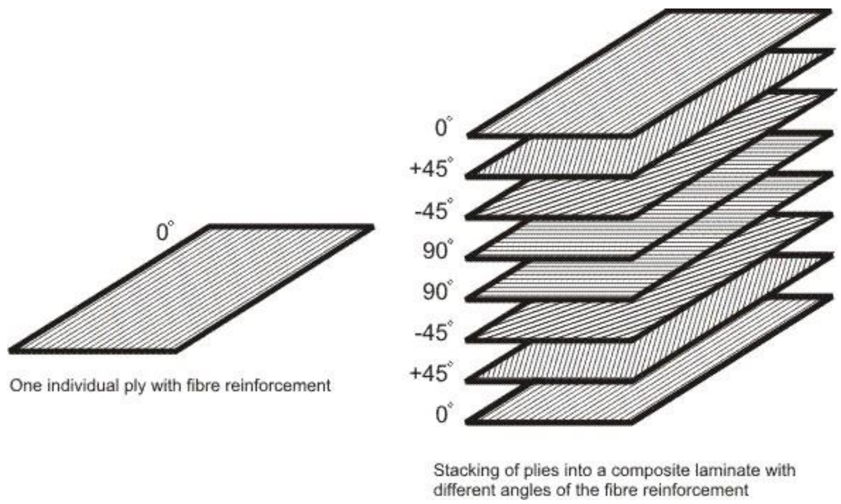

Figure 4. Image of an individual layer and a quasi-tropic lay-up or laminate. It is shown how individual layers are stacked in different orientations in order to enhance the strength and stiffness of continuous-fiber composites in different directions[4]

The fibers generally support the longitudinal tension and compression loads. These loads are disposed between the fibers by means of the matrix, which also avoids that the material may crush in compression. Inasmuch as the orientation of the fibers affects the mechanical properties of the composites, the most fibers in the direction of the main loads the better. Nonetheless, this would result in a highly anisotropic material.

[4] http://www.composites.ugent.be/home_made_composites/what_are_composites.html

In many applications, there are loads in different directions. In these cases an anisotropic material is not suitable. In order to guarantee good properties in different directions the layers are stacked up in different orientations; the most common distribution is 0°, +45°, -45°, and 90°, which can be seen in Figure 4. If the number of layers is the same in every direction, the properties are also the same in those directions. Thus, this type of composites is known as *quasi-isotropic laminates*.

4. Fiber-reinforced polymer composites

The most commonly used type of reinforcement is fibers owing to the characteristics they provide, which have already been presented in the section 3.3 Reinforcement. In regard to the materials used as matrix, the most common are polymers, and among these the thermosets. Consequently, the most common type of composites is the Fiber-Reinforced Polymer (FRP) composites, which are sometimes also known as advanced polymer composites.

The fibers that are usually used are glass, carbon, or aramid fibers, yet paper or wood or asbestos fibers have been used in some cases. The reinforcement materials that are generally used are epoxy, vinyl-ester or polyester thermosetting plastic, though phenol formaldehyde resins might also be used.

4.1. Properties of fiber reinforced polymers composites

The properties of composites obviously depend on their components and the way these are manufactured. However, there are some characteristic properties than may be found in the majority of the actual FRP composites. These most important properties are the following ones:

- Low weight
- High strength and stiffness
- Good fatigue life
- Corrosion resistance
- Good design practice
- High raw material costs
- High fabrication and assembly costs
- Anisotropic character
- Adverse effect of temperature and moisture

- Difficulty to repair
- Susceptibility to impact damage and delamination

The high strength and stiffness combined with the low weight mean that the specific strength and specific stiffness are higher than that of most metal alloys. The specific strength –also known as strength-to-weight ratio- and the specific stiffness –also known as the specific modulus or stiffness-to-weight ratio- are the strength per unit of density and modulus per unit of density, respectively.

The capacity of composites to resist cyclic loads is much higher than that of metals. Unlike metals, the fatigue strength of these materials is a high percentage of their static strength. Hence, fatigue is not a critical design factor to consider in the design of composites. The variation of the fatigue strength of different metals and that of a carbon fiber reinforced polymer are compared in Figure 5. It can be noticed, that after a large number of cycles, the strength of the metal alloys is drastically reduced, while the strength of the composite remains approximately the same.

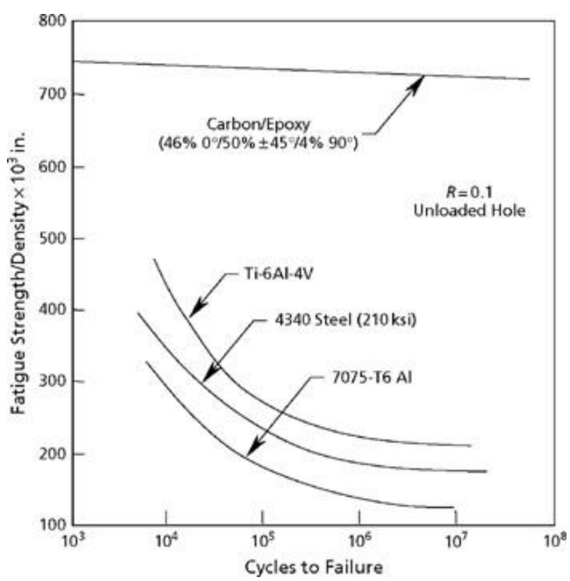

Figure 5. Fatigue properties of different aerospace materials[5]

[5] http://www.globalspec.com/reference/30805/203279/html-head-chapter-7-polymer-matrix-composites

Composite materials can delaminate due to an improper fabrication, assembly, or use. Incorrect handling or impacts may damage the structure at only one point, but the damage is highly probable to propagate through the material, causing separation between the layers.

Furthermore, most of the fibers being used as reinforcing materials are resistant to biodegradation. This fact might be an advantage during the lifetime of the corresponding application, but on the other hand can pose environmental problems. The use of natural fibers such as jute, bamboo, coir, sisal, and pineapple could be as substitute of these fibers in some cases. The natural fibers have a very high strength and are renewable and abundant. The disadvantage of using natural fibers is that they have high moisture content.

4.2. Applications

There is a huge variety of applications of composite materials. The most familiar sector of non-natural composites might be the construction using different types of concrete, as presented in the previous section. Still, the type of composites that are being the most developed at the present, are polymeric composites. The applications of these include infrastructure, transportation, automotive, aerospace…

In the aerospace sector, the weight reduction is a crucial factor. The military aircraft industry is distinguished by focusing mainly on the weight reduction despite the higher costs. As a consequence, the use of polymer composites is much higher than that in the commercial aircraft industry, even though it is increasing. The rate of composites may account for 20 to 40 percent of the airframe weight. The use of composites may decrease the weight of the aircrafts by 15 to 25 percent and thus the fuel economy is also improved. The future aircrafts build by the two most important companies in the sector, Airbus and Boeing, are expected to have a high share of high-performance composites.

Space shuttles and satellites also use relatively high amounts of high performance composites, since the price is not the main driving element. The major automakers are also increasing the use of composite materials. It is in high-performance cars and luxury cars that these materials are being used; but still not in the common cars. Some elements that are found to be made of composites are body panels, leaf springs, drive shaft, bumpers, doors, racing car bodies. In the marine sector, composites are being used in boat bodies, canoes, kayaks, etc.

Figure 6. High-performance car in which the whole exterior is made of carbon fiber[6]

In the field of infrastructures, composites may be used in roads and bridges. The current roads continuously need maintenance and reparation since they corrode. The advantages of composites are that they do not corrode, have a longer lifetime, and need much less maintenance. In addition, it is possible to build lighter bridges and even with limited earthquake damage.

Other applications include sports goods such as skis, golf clubs, tennis rackets, fishing roads; bulletproof vests and other armor parts; chemical storage tanks and other equipment; biomedical applications such as orthopedic devices; and electrical applications, for instance panels and insulators.

[6] http://www.carbonfibergear.com/excessive-carbon-fiber-cars-at-the-2013-geneva-motor-show/

4.3. Terminology

In the field of the manufacturing of fiber-reinforced polymer composites there is a specific terminology that is being used. This terminology is related to the different stages in the production of the fibers. It is thus important to consider it before going deeply into the field, in order to avoid misunderstandings. The most important definitions are introduced hereunder:

- Filament: individual fiber.
- Tow: bundles of untwisted filaments.
- Roving: number of tows joined together into a parallel bundle without twisting.
- Yarn: number of tows joined together into a parallel bundle with twisting.
- Tape: large number of parallel filaments or tows held together with an organic matrix material. Usually known as *prepeg*.
- Fabric: woven cloth made by weaving yarns or tows in various patters to provide reinforcement in two directions.

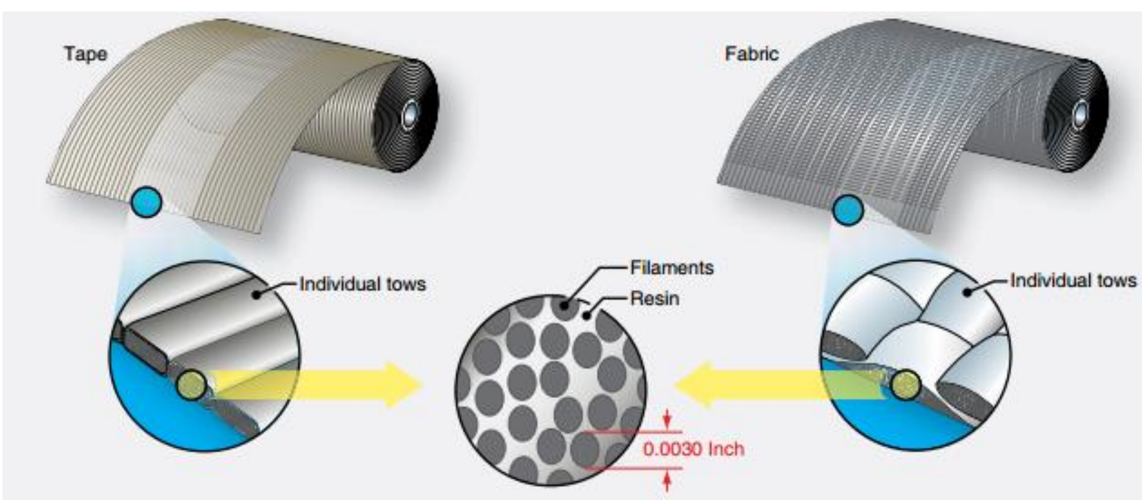

Figure 7. Tape and fabric products[7]

[7] Federal Aviation Administration, U.S. Department of Transportation

4.4. Manufacturing of the fibers in fiber-reinforced polymer composites

The manufacturing of fiber-reinforced polymer composites implies two different processes. These are the manufacturing process of the fibers, and the bonding process of the fibers with the matrix.

The manufacturing process of the fibers not only depends on the type of fibers to be used but also on how they are obtained. The most widely used fibers are glass, carbon, and aramid. All of these can be produced from different precursors and thus different methods may be used for each of the fibers.

Insofar as different types of fibers with different obtaining methods are being used, it is not possible to generalize. Even so the fibers undergo a common transformation process to enable the bonding with the matrix. To begin with, fibers are typically produced as single tows. Then, these tows undergo a textile processing technique to produce fabric types or fiber preforms. Fiber preforms are the resulting product before being bonded to the matrix. These can be sheets, continuous mats, continuous filaments, or any other shapes that suit the following processes. The most usual processing techniques of manufacturing the fiber preforms are: weaving, braiding, knitting, and stitching:

- Weaving. It can be done to produce two-dimensional fiber preforms and three-dimensional fiber preforms. These last are created by multilayer waving; however, it is difficult to have fibers oriented in other direction than 0° and 90° in this case. Figure 8 shows some of the most common two-dimensional fabric patterns.

- Braiding. It is used for the production of narrow width flat or tubular fabrics. It cannot be applied for the manufacturing of wide fabrics. Nevertheless, it does make possible to orientate the fibers at 0°, 45°, -45°, and 90°.

- Knitting. It is done with the traditional method of warp and weft. The most common is to obtain two-dimensional fabrics. However, new technics allow the production of three-dimensional fabrics.

- Stitching. It is the simples of the four techniques and the most inexpensive. It is performed by inserting a needle through a stack of fabric layers to obtain a three-dimensional structure.

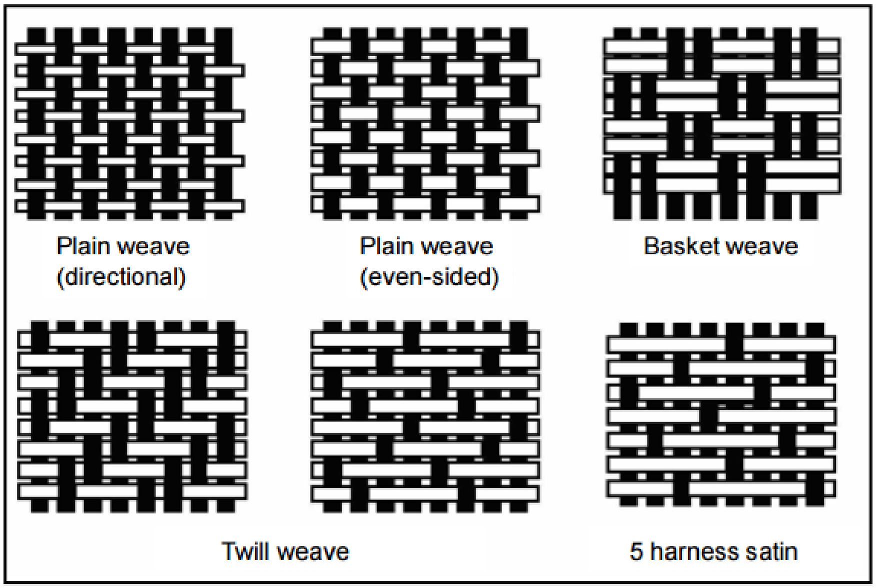

Figure 8. Different patterns of fabrics that can be used as fiber preforms[8]

4.5. Molding processes in fiber-reinforced polymer composites

The polymers used as the matrix are often referred to as resins. Thermosetting resins are the most widely-used. The resin, its chemical composition, and the physical properties affect the processing, fabrication, and the properties of the final composite material. Thermosetting resins are easily poured or formed into any shape, are compatible with most other materials, and cure into an insoluble solid. In addition, they are very good adhesives

[8] Guidebook for manufacturing CFRP Parts, Kaila

and bonding agents. The thermosetting resins that are commonly used are: polyester resins, vinyl ester resin, phenolic resin, epoxies, polyimides, polybenzimidazoles (PBI), and bismaleimides (BMI).

Thermoplastic materials can be softened and hardened repeatedly by increasing the temperature and then decreasing it again. Therefore, they can be recycled. The main advantage of these polymers is the processing speed. Chemical curing of the materials is not produced while processing, and the material can be easily shaped while it is soft.

4.5.1. Curing process of the thermosetting resins

The thermosetting polymers, also known as simply thermosets, are available in a liquid or semi-liquid form. Under the correct conditions, these undergo a chemical reaction, which is known as curing, to form a solid material. The resulting product is a solid material that will soften above a determined temperature, which is known as the glass transition temperature (Tg). Unlike thermoplastics, thermoset products do not melt but decompose with heat.

The first step to be done to perform the curing is to mix the thermoset resin with a hardener. Throughout the curing process the resin will pass from a liquid state, through a gel state, to a solid state. The cure time is defined as the time needed to curry out all the curing process.

- Liquid – open time. It is the time during which the resin remains a liquid after it has been mixed with the hardener. The assemblies and the clamping should be done during this time, since the mixture will become more viscous until it reaches a gel state and cannot flow any longer.

- Gel – initial cure. The mixture becomes a gel and it is not workable any more. This is known as the gel point. It continues to harden until it reaches a solid state.

- Solid – final cure. The mixture has cured to a solid state after the cure time and can be dry sanded and shaped. The resin has a 90% of the maximum strength, which will be reached after some more days. The clamps can already be removed.

The ideal temperature of the curing process depends on the hardener. The process of curing may be performed at different temperatures but this implies different cure times. The higher the temperature of the resin, the faster it cures, as seen in Figure 9. Moreover, the chemical reaction of curing produces exothermic heat that depends on the thickness of the surface. In thick structures more heat is retained and thus the cure time is reduced. Furthermore, the curing at high temperatures increases the end mechanical properties of the material.

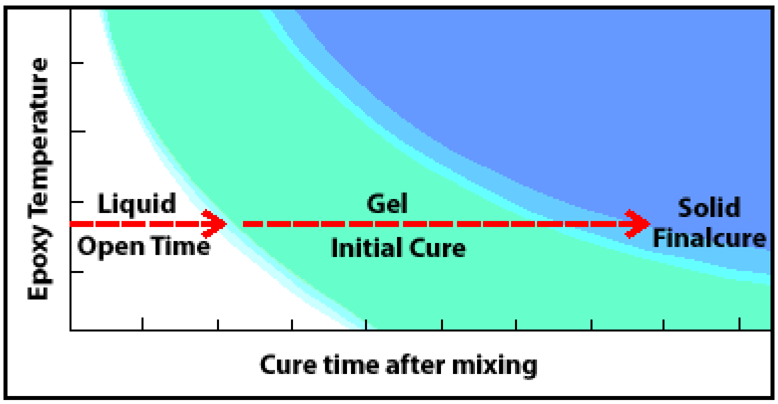

Figure 9. Example of the state of epoxy during the curing based on the temperature and the time. As epoxy cures it passes from liquid state, through a gel state, to a solid state[9]

4.5.2. Molding

There is a wide range of processes that may be used for the molding of FRP. These provide different rates of flexibility, properties, and production costs. The leading processes are the matched die molding, the contact molding, and other significant molding methods.

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[9] http://www.westsystem.com/ss/epoxy-chemistry/

Matched die molding

This type of methods produces highly consistent, net-shape and near-net shape parts with two finished surfaces and low labor cost. The molding methods included in this category are:

- Compression Molding. It is the most common molding process for high-volume FRP parts. It produces high-strength, complex parts in a wide variety of sizes. Matched metal molds are mounted in a molding press. The molds are heated and pressure is applied.

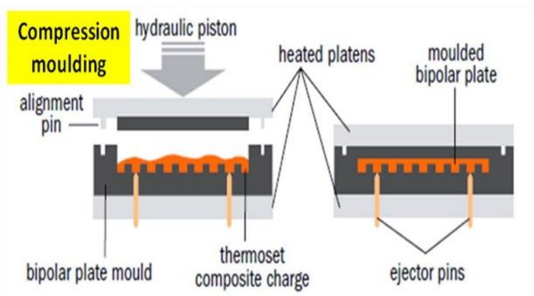

Figure 10. Compression Molding[10]

- Low Pressure – Low Temperature Compression Molding. This method uses composite molds instead of metal molds, which may or may not be heated. It is a more inexpensive molding method yet only suited for simple shapes.
- Transfer Compression Molding. In this process the molding is done using a transfer cylinder. It is best suited for very thick parts, such as transformer bobbins.
- Resin Transfer Molding. This is an intermediate process between the slow spray-up and the faster compression-molding. The fabric is placed in the mold, which is then

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[10] http://www.intechopen.com/books/nanocomposites-with-unique-properties-and-applications-in-medicine-and-industry/a-review-of-thermoplastic-composites-for-bipolar-plate-materials-in-pem-fuel-cells

closed and clamped. The resin is pumped in under pressure displacing the air until the mold is filled. It is appropriate for medium-volume production FRPs.

- Injection Molding. This method is suitable for both thermosets and thermoplastics. The difference lies in the temperature kept in various areas of the system, especially in the injection screw and the chamber.

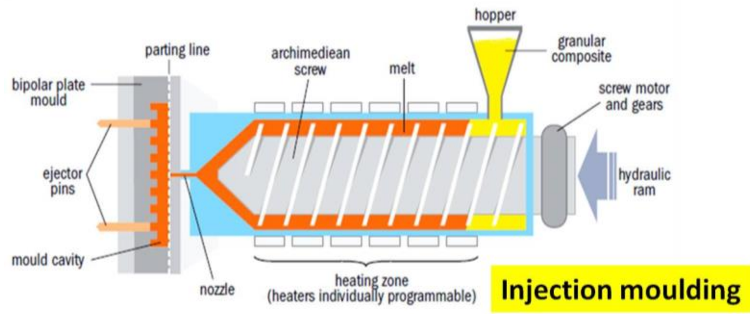

Figure 11. Injection Molding[11]

- Structural Reaction Injection Molding. This method is similar to injection molding but it uses a preform or reinforcing fabric instead.

Contact molding methods

This type of methods is also known as open mold methods. This type of methods is simpler and allows for manufacturing FRP with only one finished surface at a lower cost. The molding methods included in this category are:

[11] *http://www.intechopen.com/books/nanocomposites-with-unique-properties-and-applications-in-medicine-and-industry/a-review-of-thermoplastic-composites-for-bipolar-plate-materials-in-pem-fuel-cells*

- Hand Lay-Up. This is the simplest and oldest molding method. It is used for low-volume production of large pieces such as boat hulls. This method has three stages: firstly, a gel coat is sprayed onto the mold for a high-quality surface; then, the fabric is placed onto the mold; and, finally, a resin is poured or sprayed on. Additional layers are used to thicken the structure. The cure during the molding process can occur without external heat.

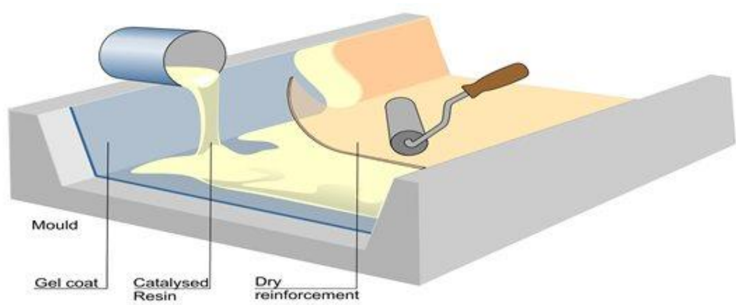

Figure 12. Hand Lay-Up Molding Method[12]

- Spray-Up. This process is similar to hand lay-up. The difference is that the resin is deposited in the mold from a spray gun.

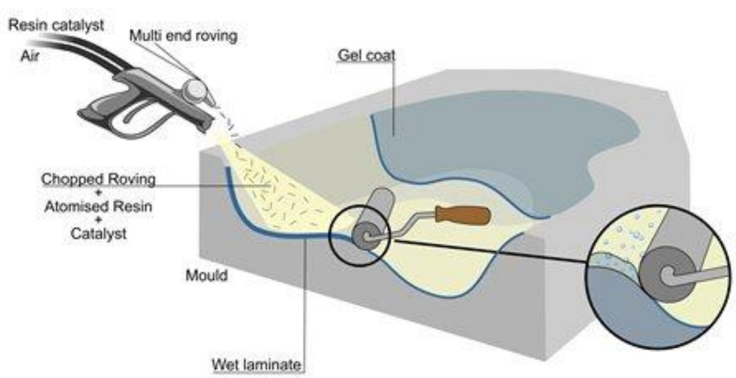

Figure 13. Spray-Up Molding Method[13]

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[12] http://www.nuplex.com/composites/processes/hand-lay-up

- Vacuum Bag Molding. In this method a film is placed over the lay-up forming a bag. Next, the vacuum is drawn in it to eliminate the entrapped air and the excess resin. The cure can also occur without external heat. The advantage of this method is higher reinforcement concentration and better adhesion between layers.
- Vacuum Infusion Molding. This process is similar to vacuum bag molding. The difference is that the fabric is placed on the mold and the resin is introduced when drawing the vacuum. It allows for the production of very large parts.
- Autoclave Molding. This process is a further modification of the vacuum bag molding. In this case, heat and pressure are used in the cure.

[13] http://www.nuplex.com/composites/processes/spray-up

5. Carbon fiber reinforced polymer

Carbon Fiber Reinforced Polymer (CFRP) has become one of the most important fiber-reinforced polymer composites in recent years. The CFRP industry has been growing steadily to meet the demands in an increasing number of applications like aerospace, military, turbine blades, automobile, and sporting goods, among others. The CFRPs consist of a reinforcement of carbon fibers and a matrix that is usually of epoxy.

The use of CFRPs is predominant in high-performance structures where the cost is not the main factor to consider. The most used fibers in FRP are glass, aramid, and carbon; other fibers that are also used are S-2 glass and E-glass fibers. The cost of the fibers in descending order is: carbon, graphite, aramid, S-2 glass, and E-glass. Consequently, carbon and graphite fibers are used in the case where high performance is to be achieved.

5.1. Carbon and graphite fibers

Carbon and graphite fibers may be manufactured with different properties; however, the most noticeable are those that are typical for fibers, such as high tensile and compressive strength, high module, outstanding fatigue life, and no corrosion. The names of carbon fibers and graphite fibers are sometimes misused. The difference between them falls on the manufacturing techniques.

The temperature at which graphite and carbon fibers are treated are different; graphite fibers at exposed at temperatures above 1650°C while carbon fibers are exposed at lower temperatures. The content of carbon in the fibers is also a distinguishing factor; carbon content in graphite fibers is higher than 99 percent whereas in carbon fibers it varies between 93 and 95 percent.

The graphite structure consists of layers of carbon atoms. Each of the carbon atoms in one layer is bonded with three other carbon atoms on the same layer by means of a covalent bond forming hexagonal structures. The layers or planes of the graphite structure are hold together by weak van der Waals bonds. The superior strength and moduli of graphite and carbon fibers is given by the very strong covalent bonds along the structures. Carbon fibers consist of both graphite and non-graphitic carbonaceous material.

Carbon and graphite fibers are remarkably anisotropic. This is consequence of the structure of graphite. The strength in the longitudinal direction, that is to say in the direction of the layers, is much higher than the strength in the transversal direction. In the longitudinal direction the strong covalent bonds support the loads whereas in the transversal direction it is the weak van der Waals bonds. The longitudinal strength can be more than 28 times higher than the transversal strength.

5.2. Classification of carbon fibers

Carbon and graphite fibers can be produced from different precursor fiber materials: polyacrylonitrile (PAN) fibers, rayon fibers, and petroleum-based pitch fibers, among others. Based on this, carbon fibers may be classified into PAN-based carbon fibers, rayon-based carbon fibers, and pitch-based carbon fibers. The most common for structural applications despite being the most expensive are the PAN-based carbon fibers since the carbon yield is almost double that of rayon fibers. Actually, PAN-based carbon fiber account for almost 90 percent of the total manufactured carbon fibers. All the precursors used are organic polymers that consist of long strings of molecules bound together by carbon atoms.

Carbon fibers may also be classified based on their properties. This leads to the following groups: ultra-high modulus (UHM), high-modulus (HM), intermediate-modulus (IM), low modulus and high-tensile (HT), and super high-tensile (SHT). UHM fibers have a modulus higher than 450 GPa, HM fibers have a modulus between 350 and 450 GPa, IM fibers have a modulus between 200 and 350 GPa, HT fibers have a modulus lower than 100 GPa and a tensile strength higher than 3.0 GPa, and SHT fibers have a tensile strength higher than 4.5 GPa.

Another classification of carbon fibers is based on the final heat treatment. This has a direct impact on the properties of the fibers. The following groups may be found: type-I, high-heat-treatment carbon fibers (HTT); type-II, intermediate-heat-treatment carbon fibers (IHT), and type-III, low-heat-treatment carbon fibers (LHT). HTT fibers are treated at a temperature higher than 2000°C; these usually have a high modulus. IHT fibers are treated at a temperature around 1500°C; these have a high strength. LHT fibers are treated at a temperature lower than 1000°C; these have a low modulus and low strength.

5.3. Manufacturing of carbon and graphite fibers

The process of manufacturing carbon and graphite fibers depends on the type of precursors that are being used and the properties to be achieved. The specific composition of the fibers depends on the manufacturer, and is usually a professional secret. There are some steps of the manufacturing process that are common for the different type of precursors, even if they are not exactly performed the same way. These are stabilization of the precursor, carbonization, graphitization, and post-treatments. The processes are partly chemical and partly mechanical and different gases and liquids are utilized. These might be utilized to react with the fibers or to prevent certain reactions, depending on the desired effect.

The process of stabilization consists in a steady and continuous decrease of the diameter of the fibers and linear density. Throughout this process there may be a change in the color of the fibers. The process of carbonization consists in heating the long strands or fibers at a high temperature, without oxygen to avoid them to burn. During this process the atoms in the fibers vibrate strongly and the majority of the non-carbon atoms are ejected. The result of this process is long, interlocked chains of carbon atoms. These have scarcely any non-carbon atom. At this stage, the carbon fibers can undergo a process known as graphitization during which they can be heated to temperatures of more than 2000°C in order to achieve a higher modulus. The crystalline orientation, the interlayer spacing, and the ordered structure depend on the heat treatment temperature.

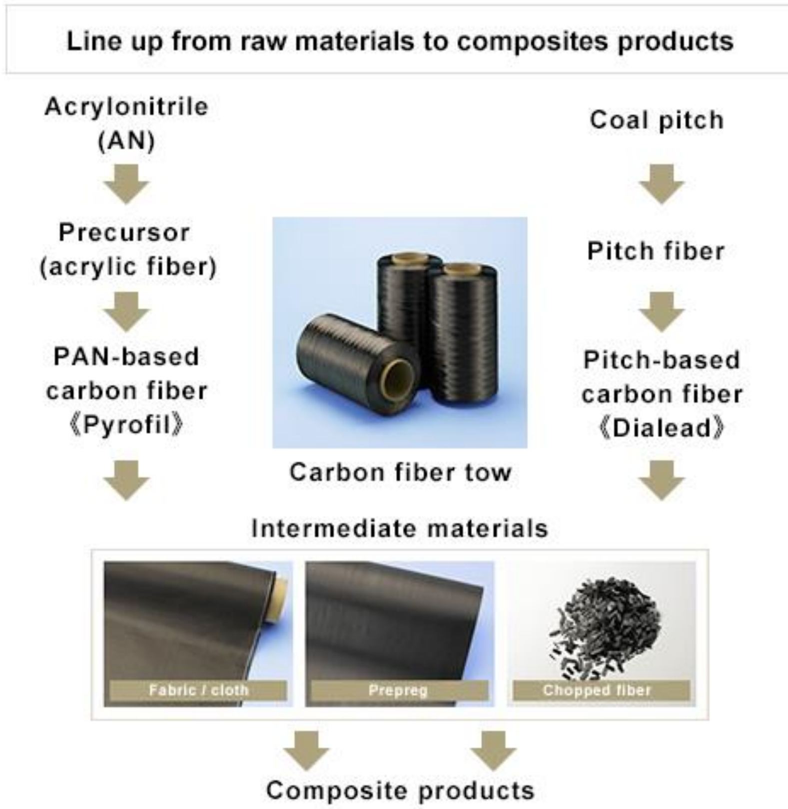

Figure 14. Procedure of manufacturing carbon fibers[14]

5.3.1. Rayon-Based Fibers

Rayon-based fibers are produced from naturally occurring cellulose polymers from wood pulp. The main characteristics of rayon fibers are their availability, low cost, non-melting character, and ease of production. Nevertheless, the availability of suitable rayon precursor is decreasing and the carbon content in rayon fibers is quite low, around 44 percent. The process of converting rayon fibers to carbon fibers consists of three phases: stabilization, carbonization, and graphitization.

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[14] https://www.mrc.co.jp/english/products/special/

The stabilization process takes place in three steps. The rayon fibers are first subjected to a process of desorption at a temperature between 25°C and 150°C. Next, there is a dehydration of the cellulosic unit at a temperature between 150°C and 240°C. Finally, the fibers undergo a heat treatment that takes place at a temperature between 205°C and 410°C.

The carbonization process takes place at a temperature between 400°C and 700°C. During this phase the carbonaceous residue is converted into a graphite-like layer. This process, unlike that of PAN-based carbon fibers and pitch-based carbon fiber, does require neither stretching nor melting before.

The graphitization process is to carry out an ordering of the fibers through longitudinal orientation of the planes. It is usually performed at a temperature between 700°C and 2700°C. However, the alignment is poorer than in PAN-based and pitch-based carbon fibers, and thus the fibers may be treated at temperatures up to 3000°C.

5.3.2. PAN-Based Fibers

PAN-based fibers are produced from polyacrylonitrile (PAN). PAN is a synthetic resin formed by the polymerization of acrylonitrile. It is a hard, rigid thermoplastic material that is resistant to most solvents and chemicals. This decomposes before melting and it is necessary to make a solution sing a solvent before the spinning.

PAN-based carbon fibers have a better orientation in the raw precursor form and much higher yields of approximately 50%. The production of these fibers consists of five steps:

- Spinning and stretching the PAN to form a fiber.
- Stabilization and oxidation in air at 200 to 300°C under tension.
- Carbonization in an inert atmosphere at 980 to 1595°C.
- Graphitization in an inert atmosphere at 1980 to 3040°C
- Surface treatment and sizing.

In the spinning process acrylonitrile plastic powder is mixed with another plastic to make a solution since PAN decomposes before melting. Then the spinning into fibers is done using different methods, which can be either dry or wet; currently the wet-spun process is more common. In some methods the plastic is mixed with some chemicals and pumped through tiny jets into a chemical bath or quench chamber where the plastic coagulates and solidifies into fibers. In other methods, the plastic mixture is heated and pumped through tiny jets into a chamber where the solvents evaporate leaving a solid fiber. Throughout the spinning process the internal atomic structure of the fiber is formed and the fibers are lengthened from 500 to 1300%. This is an indispensable process to achieve a high strength because it arranges the molecules within the fiber to prepare the bases for the following step.

The stabilizing process is performed before carbonization to avoid the melting of the fibers during this last process. In the stabilization the fibers are chemically altered by a heat treatment at 200 to 300°C for 30 to 120 minutes. The thermoplastic PAN is converted into a non-plastic compound that is capable of withstanding high temperatures.

The carbonization process is performed in a gas mixture atmosphere, which is usually mainly nitrogen, at a temperature of 980°C to 1595°C. During the heating process the fibers lose their non-carbon atoms, and they contract in diameter and lose around 50 percent of their weight.

The carbonization process is performed in gas mixture atmosphere from a temperature of 1000°C to 3000°C. This process is normally carried out in a nitrogen atmosphere at a temperature of 980°C to 1595°C. During the heating process the fibers lose their non-carbon atoms, and they contract in diameter and lose around 50 percent of their weight. The graphitization process is also performed in a gas mixture atmosphere as a continuation of the carbonization process. This is carried out at a temperature than can be up to 3000°C for several minutes.

Last but not least, surface treatments and sizing are performed. The fibers are coated to protect them from damage during winding or weaving. Furthermore, they are wounded onto bobbins.

The heat treatments that have to be undergone are responsible for the high costs of the carbon fibers. The higher the modulus of the fibers the higher the temperatures have to be. This way, greater amounts of aligned graphite are produced.

5.3.3. Pitch-Based Fibers

Pitch-based fibers are produced from pitches that are given a heat treatment. These are complex blends of polyaromatic molecules and heterocyclic compounds, which may have a content of carbon higher than 80 percent. There are different sources from which these pitches can be obtained: petroleum refining or asphalt; destructive distillation of coal; natural asphalt; and pyrolysis of PVC. The most common pitches used for the production of carbon and graphite fibers are petroleum pitch and coal tar pitch.

Petroleum pitch can be obtained from different sources such as heavy residue. The chemical and physical properties of this pitch are determined on the process and conditions employed. The most important factors affecting the properties are the heat process' temperature and time.

Coal tar is a by-product of the cocking of bituminous coals to produce cokes. Coal tar pitch is obtained from this using distillation and heat treatment processes. The resulting pitches are complex mixtures containing a large variety of organic compounds. The compositions and characteristics depend on the source of the tar and the method of obtaining.

In order to manufacture carbon fibers from pitch-based precursor, it is necessary to prepare these precursors. The preparation process of petroleum pitch and coal tar pitch are different, but both are based on heat treatments. The advantages of using pitch as a precursor for the manufacture of carbon fiber is that they have a lower material cost, a higher char yield, and a higher degree of orientation compared to those of PAN. In addition, the graphitic structure of the pitch-based fibers gives them a higher elastic modulus, and higher thermal and electrical conductivity. Nevertheless, the cost to obtain high-performance carbon fibers is higher.

The process to manufacture carbon fibers consists of the typical steps: production, stabilization, carbonization, and graphitization of the precursor fibers, and then post-treatments. The most influential process is stabilization since only correctly stabilized fibers can assure the adequate performance of the resulting carbon fibers.

Table 1. Properties of some commercially important high-strength fibers[15]

Type of fiber	Tensile strength, GPa	Tensile modulus, GPa	Elongation at failure, %	Density, g/cm^2	Coefficient of thermal expansion, 10^{-6} °C	Fiber diameter, μm
PAN-BASED CARBON						
Standard modulus	3.45-4.83	221-241	1.5-2.2	1.80	-0.4	6-8
Intermediate modulus	4.14-6.21	276-296	1.3-2.0	1.80	-0.6	5-6
High modulus	4.14-5.52	345-448	0.7-1.0	1.90	-0.75	5-8
PITCHED-BASED CARBON						
Low modulus	1.38-3.10	172-241	0.9	1.9	-	11
High modulus	1.90-2.76	379-621	0.5	2.0	-0.9	11
Ultra-high modulus	2.41	690-965	0.3	2.2	-1.6	10

[15] Campbell (2010)

5.4. Mechanical properties of carbon fiber composites

CFRP is light and extremely strong. Its specific tensile strength and specific elastic modulus are higher than that of glass fiber reinforced polymer or steel. Actually, CFRP have a relative stiffness five times that of steel. The modulus of CFRP is typically 138 GPa and the tensile strength 3.5 GPa.

The fatigue resistance of CFRP is much higher than that of metals and other structural materials. In Figure 5 the fatigue resistance of CFRP is compared to that of some metals.

CFRP have low heat expansion ration and high dimensional stability, and keeps its mechanical properties even at high temperatures. A typical CFRP consisting of epoxy with intermediate modulus carbon fibers cures at 175°C. This has an acceptable use up to 150°C, but it is often restricted to 120°C.

Furthermore, CFRP has a high electric conductivity and magnificent X-ray permeability.

Table 2. Comparison of the mechanical properties of CFRP and metallic materials[16]

Material	Density ρ [g/mm^3]	Tensile Modulus E [GPa]	Tensile Strength σ [MPa]	Specific Modulus (E/ρ)	Specific Strength (σ/ρ)
Aluminum 7075 T6	0.0028	72	570	25.7	203.6
Titanium 6Al 4V	0.0045	114	1000	25.3	222.2
Steel Maraging 300	0.0080	207	2000	25.9	250.0
Carbon/Epoxy M46J UD	0.0018	250	1415	138.9	786.1
Carbon/Epoxy T800 UD	0.0018	154	2570	85.6	1427.8

[16] https://www.highpowermedia.com/F1-Monitor/3648/not-composite-yet

6. Case: Baltic Yachts

Baltic Yacths is a company that designs and builds some of the most hi-tech, high-performance sailing yachts in the world. It was started up in 1973 by PG Johansson, Nils Luoma, Tor Hinders, Jan-Erik Nyfelt and Ingmar Sundelin. The initial shipyard site was situated in Bosund, in Ostrobothnia region, in Western Finland. The company has managed to go through financial crises and ownership changes throughout its history specially by investing in the development of new technology.

In the beginning, the most focus was put into design and production. For this reason, no marketing strategy was implemented but yet contracts with important partners were established, being the most relevant with the Canadian company C&C Design. This company had experience in building racing boats and using lightweight sandwich construction, and Baltic Yatchs made a contract with for 10 boats.

The first Baltic Yatchs' boats were equipped with advanced technology that was not found in the competition, for instance they had epoxy-glued teak decks, and sandwich construction in both the hull and the deck. Actually, the boats build in the 1970s are still more advanced than many serial production boats of today. In 1979 Baltic Yatchs was already using carbon fiber parts in production; in 1995 the first boat completely made of carbon fiber was manufactured.

The philosophy within the company is to be at the vanguard of the technological development since it is the way to produce the best boats. Brainstorm meetings were a regular basis in order to get new ideas. From an early stage, Baltic Yacths introduced computer technology into the design process. In fact, as soon as the 1970s, computers were being used for different tasks. Needless to say, today computer programs are a key component in the design process to provide robustness and quality.

Baltic Yatchs continued to grow during the 1970s and early 1980s, by means of product development and production, and investments in the subsidiary's marketing. In addition, a sales office was opened in the U.S.A. Nevertheless, in the late 1980s the company was hit by a decrease in the demand. This brought a change in the ownership, from the owner at the moment to workers that became co-owners. The company handled to overcome the difficulties by remaining true to its principles.

In the 1990s there was a rise in the demand for bigger boats, especially from owners who had already had a boat from the company. Thus, Baltic Yatchs started to build boats that were more than 100 foot long. The first one set sail in 2002. In the early 2000s, new facilities in the port of Jakobstad were opened. These have been fundamental for the building of the biggest projects of Baltic Yachts. In 2010 and 2013 there were some changes in the ownership, and 80 percent stake of the company now belongs to Ottobock.

At the moment, Baltic Yachts designs and builds high-performance sailing boats that are exclusive, unique, and with superb quality material, which can be up to 200 foot. The latest high-tech materials and methods are being used so as to build light and strong yachts. The use of ultra-light durable composite constructions, specially the use of carbon fiber, entails that the boats are more environmental friendly since they are lightweight and thus the needs for energy are reduced. The yachts are currently being built in the production plants in Jakobstad and Bosund. In addition, a Baltic Lifecycle Service center has been recently set up in Palma de Mallorca, Spain.

Figure 15. Baltic 112 NILAYA built by Baltic Yacths

7. Introduction to the production process at Baltic Yachts

The whole process of designing and building the CFRP yachts takes place in the facilities of Baltic Yachts in Jakobstad and Bosund. The design of a yacht may take as long as three years, and the building may take up to almost on year. The hull and the structure of the yachts are currently entirely made of CFRP.

The carbon fibers are not produced within Baltic Yachts. The raw materials used are carbon fiber that is usually bought in the form of fabric and epoxy resin. The fabrics may have different patterns and tows in different orientations based on the loads that have to be supported. Thus, the type of fabric that is used depends on the part of the yacht that is being manufactured.

In this company, epoxy resin is used as the matrix in this CFRP. The carbon fiber fabrics are poured with liquid or semi-liquid epoxy resin. The number of layers of carbon fiber fabrics and epoxy resin that are held together depends on the desired properties, which depend on the thickness. The carbon fiber fabrics together with the epoxy resin have to undergo a process of curing and molding, as explained hereinabove.

The process of curing and molding of the hull and the structure is performed in different steps and dividing them into parts owing to the total dimensions. The carbon fiber fabrics are poured with the epoxy resin and then placed into a mold with the desired shape of the hull. The molding method is a modification of Hand Lay-Up, which is also known as Open Molding. In order to accelerate the process of curing a heat treatment is applied.

The heat treatment is executed by placing the mold with the raw CFRP in an oven. Actually, a wooden structure is placed integrating the mold inside. This oven then looks like a sauna, and is heated by means of heating fans. The temperature to be reached is between 80°C and 90°C. This should be uniform throughout all the surface of the CFRP so as to ensure the same properties in all the structure and hull.

The next step is to dismantle the oven and the mold. At this point the CFRP has enough strength and stiffness so as not to require the mold. Despite this fact, it does not have the final strength and stiffness because the curing process is not completed. At this point the different parts of the hall are put together and joined. The curing process is continued by applying another heat treatment. This consists in putting electrical blankets on the CFRP to heat it up again. The temperature to be achieved is 115°C. After this last process the hall may be painted or applied any superficial treatment to get the requested finishes.

8. Theoretical introduction to the experimental part

The main objective of the thesis is to study the heating of carbon fiber by means of electricity. This will be done by using the carbon fibers as conductors, so electricity would be conducted through them. Therefore some introduction to electricity is needed to follow the experimental part.

8.1. Introduction to electricity

Electrical current is defined as the flow of charged electrons. The most common types of currents are direct current (DC) and alternating current (AC). The difference between DC and AC is found in the direction of the flow. The DC is constant and moves in one direction whereas AC changes over time in a periodic repetition. The AC graph makes a sinusoidal pattern.

Ohm's establishes the relation between the current through a conductor, the voltage between the opposite ends, and its electrical resistance. The current is directly proportional to the voltage and inversely proportional to the resistance. The mathematical equation describing this law is:

$$I = \frac{V}{R}$$

where I is the current or intensity in amperes (A), V is the voltage in volts (V), and R is the resistance in ohms (Ω). This law can be applied to any DC circuit. In AC, when there are inductors, capacitor, or transmission lines, this formula cannot directly be applied. In that case, the inductance or capacitance shall be taken into account.

8.2. Resistance variation depending on the temperature

The resistance of a conductor depends on the size of the conductor, but also depends on the temperature of the conductor. This fact is related to the expansion and contraction of the materials with the temperature.

The materials are usually classified between conductors and insulators. Conductors are those that easily conduct electricity while insulators are those that hardly conduct electricity. Conductors tend to increase their resistance with an increase in temperature; insulators tend to decrease their resistance with an increase in temperature.¨

The electrical behavior of semiconductor materials depend upon if they are intrinsic or extrinsic, that is to say if they are pure or they contain impurities. However, all semiconductor materials are distinguished by decreasing their resistance with an increase in temperature. The difference between intrinsic and extrinsic is the rate their resistance is changed.

PART 3: EXPERIMENTAL PART

9. Objective

The objective of this part is to study by means of tests the heating of CFRP using electricity. In the company Baltic Yachts the CFRP is heated in two stages as part of the curing and molding process. The heat treatment is high time and energy consuming due to steps of the process, explained hereinabove in section 7.Introduction to the production process at Baltic .

The heat treatment process includes the building and the dismantling of the oven for every use. The yachts are not mass-produced, and so the oven itself cannot be reused with the same dimensions, and obviously this requires time and energy. The elements of the oven, however, are evidently reused when building it again. Regarding the mold, this is hardly ever reused because every yacht is unique, and so the molds are destroyed. Moreover, the process of heating itself does require large amounts of energy as the whole oven is heated. This implies that not only the raw CFRP is heated, which is the actual goal, but also the inside air and the walls.

In order to reduce the energy and the time used in this process, the company Baltic Yachts wanted to study the possibility of heating the CFRP by means of electricity. Thus, it is to study to conduct electricity through the carbon fiber so as to heat the whole CFRP structure. In this section different tests will be carried out so as to perform the study.

10. Method

The development of this experimental part included some visits to the facilities of the company Baltic Yachts in Jakobstad. The aim of the first visit was to get to know the company and the production manager. This visit included a tour through the facilities with the corresponding explanation of the manufacturing process of the yachts and, more in detail, the treatment of the CFRP. In addition, a series of samples of carbon fiber were offered. These samples were raw carbon fiber fabrics with different orientations and distributions. The samples can be seen in the following pictures:

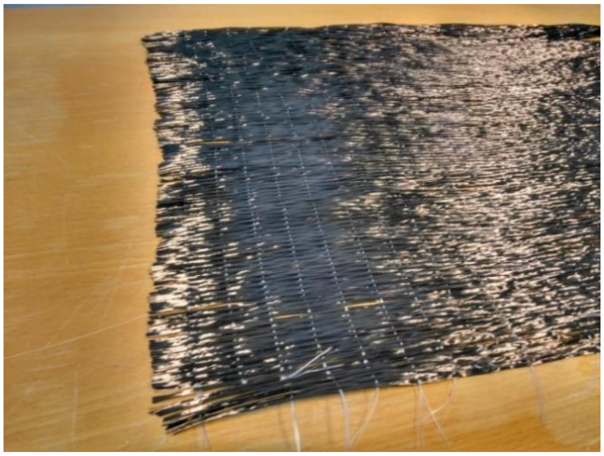

Figure 16. Carbon fiber fabric with unidirectional tows

Figure 17. Carbon fiber fabric with multidirectional tows

Figure 18. Carbon fiber fabric with multidirectional tows

Figure 19. Carbon fiber tows held together in a resin

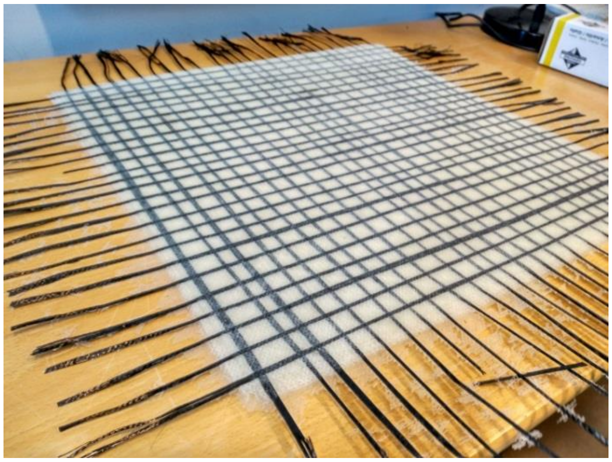

Figure 20. Carbon fiber tows held together in a resin

Three different tests were conducted to study the feasibility of heating carbon fiber by means of electricity. The strategy throughout this part has been modified according to the progress. It has already been stated that the first action that was taken was to visit the company. The explanations and the samples resulted in the conclusion that is would be necessary to use an electronics laboratory. In this case the laboratory used is situated in Technobothnia Education and Research Center, which is shared between University of Vaasa, Vaasa University of Applied Sciences (VAMK), and Novia University of Applied Sciences.

10.1. Test 1

The goal of the first test was to have a first observation of the behavior of the raw carbon fiber samples when electricity is conducted through them. Actually, the focus was on the behavior of single tows of carbon fibers. This and the other tests are evidently explained in more detail in the following sections. This test was to get used to the heating of the carbon fibers with the electricity. It was carried out by using some carbon fiber tows as an electrical conductor, and taking some basic measures on the voltage and current through the tows. No specific conclusion was being sought; however, an interesting fact was discovered: the variation of the resistance dependent on the temperature is similar to that of semiconductors.

10.2. Test 2

The performance of the first experiment was a motivation to continue with studying the conduction of electricity throughout a single tow. The second experiment consisted, thus, in heating up one tow, but in this case taking measures of the temperature in function of the voltage and the current applied. Therefore, what was done was mainly to heat two tows until they started to burn. In this case, the goal was to get more precise information on the voltage and current needed to achieve the desired temperature.

10.3. Test 3

The goal of this test was to heat more than one tow at the same time. In the previous tests it was checked that it was possible to heat one carbon fiber tow and which approximate voltage and current was necessary for a certain length. In order to perform this experiment the company supplied one sample with parallel carbon fiber tows with a separation between them that were held together with a resin and another sample with parallel carbon fiber tows with the same distribution but in two directions. These samples are shown in Figure 19 and Figure 20. In addition, two metal plates were also supplied to be able to connect the tows to a generator.

11. Development of test 1

11.1. Equipment

- Raw carbon fiber tows
- Voltmeter
- Ammeter
- Generator

11.2. Procedure

1. A tow of carbon fiber is taken in order to be heated.
2. The tow of carbon fiber is connected in series with the ammeter and in parallel with the voltmeter.
3. One extreme of the carbon fiber tow is connected to the positive pole of the generator.
4. The other extreme of the carbon fiber tow is connected to the negative pole of the generator.
5. The generator is turned on.
6. The voltage supplied by the generator is varied in order to observe the effects on the carbon fiber tow.
7. The resistance of the tow is calculated.
8. The resistance per unit of length of the tow is calculated based on the length of the carbon fiber tow so as to be able to compare the values with tows of other lengths.

11.3. Results

The results of the experiment –intensity values per different voltage values- are shown in the following table. The resistance of the carbon fiber sample is calculated from these values by means of the Ohm's law.

Table 3. Results of the test 1: voltage and intensity values. Values of the resistance and the resistance per unit of length are calculated from those values. Length of the fiber.

DATA EXPERIMENT 10/02/2016 9:00			
Voltage (V)	Intensity (A)	Resistance (Ω)	Resistance (Ω/m)
0.5	0.058	8.6	37.5
3.0	0.36	8.3	36.2
7.0	0.87	8.0	35.0
9.0	1.14	7.9	34.3
10.0	1.28	7.8	34.0
11.0	1.43	7.7	33.4
12.0	1.57	7.6	33.2
13.0	1.72	7.6	32.9
14.0	1.86	7.5	32.7
15.0	2.02	7.4	32.3
16.0	2.18	7.3	31.9
17.0	2.33	7.3	31.7
18.0	2.49	7.2	31.4
19.0	2.65	7.2	31.2
20.0	2.83	7.1	30.7
23±1 cm			

11.4. Conclusions

The intensity passing through the carbon fiber filament increases while the voltage supplied increases. The results of the resistance show that it is not constant but decreases. Joule's first law states that electricity passing through a conductor produces heat equal to the product of the resistance of the conductor, the square of the current, and the time for which it flows. Therefore, the temperature of the filament increases with the voltage, which was noticed during the experiment.

Thus, the resistance of the carbon fiber tow is reduced when the temperature increases. Generally, conductive materials tend to increase their resistance with an increase in temperature. However, the resistance of semiconductors decreases with an increase in temperature. Hence, carbon fiber filaments behave like a semiconductor material.

12. Development of test 2

12.1. Materials

- Raw carbon fiber tows
- Voltmeter
- Ammeter
- Generator
- Infrared thermometer

12.2. Procedure

1. A tow of carbon fiber is taken in order to be heated.
2. The tow of carbon fiber is connected in series with the ammeter and in parallel with the voltmeter.
3. One extreme of the carbon fiber tow is connected to the positive pole of the generator.
4. The other extreme of the carbon fiber tow is connected to the negative pole of the generator.
5. The generator is turned on.
6. The voltage supplied by the generator is varied in order to observe the effects on the carbon fiber filament.
7. The temperature of the tow is measured.
8. In this case, the experiment is repeated twice. The first time, using the carbon fiber tow from experiment 1, and the second time using another carbon fiber tow.

12.3. Results

The results of the experiment –intensity and temperature values per different voltage values- are shown in the following tables. The results in the Table 4 correspond to the carbon fiber tow used in test 1 and the results in Table 5 correspond to the other carbon fiber tow. The temperatures that are presented in Table 5 are the maximum and minimum temperatures of the tow.

Table 4. Results of the test 2: voltage, intensity, and temperature values. Length of the fiber.

DATA EXPERIMENT 18/02/2016 9:00		
Voltage (V)	Intensity (A)	Temperature (°C)
0.0	0.00	23
6.9	0.83	69
8.2	1.00	84
10.1	1.25	103
10.8	1.35	113
11.5	1.45	123
12.2	1.55	142
12.9	1.65	154
13.7	1.76	164
14.4	1.86	175
15.0	1.95	190
15.7	2.05	200
16.3	2.15	218
17.3	2.25	204
18.0	2.40	244
23 cm		

Table 5. Results of the test 2: voltage, intensity, and temperature values. Length of the fiber.

DATA EXPERIMENT 18/02/2016 9:30			
Voltage (V)	Intensity (A)	Max. Temperature (°C)	Min. Temperature (°C)
0.0	0.00	23	23
1.2	0.10	27	24
2.3	0.20	28	24
3.4	0.30	30	30
4.6	0.40	36	33
5.6	0.50	44	42
6.7	0.60	52	50
7.7	0.70	62	59
8.7	0.80	77	69
9.7	0.90	84	74
10.6	1.00	91	86
11.6	1.11	103	100
12.5	1.20	120	104
13.4	1.31	130	117
14.3	1.40	140	128
30.4 cm			

12.4. Conclusions

The main conclusion of this experiment is that the temperature is not constant through the tow when it conducts electricity. This fact might be attributed to different possibilities: the relatively short length of the tow; a bad connection where it heats up more; an error in the measure using the infrared thermometer due to the small area of the tow compared to the area of measurement; or impact of the temperature of the table on which the test was performed.

13. Development of test 3

13.1. Materials

- Raw carbon fiber tows held together
- Four metal plates
- Voltmeter
- Ammeter
- Generator
- Infrared thermometer
- Clamps

13.2. Procedure

1. Two plates are placed on one of the sides of the sample. These are placed with the carbon fiber tows between them.
2. Two or more clamps are mounted pressing together the plates.
3. The other two plates are placed with the same configuration at the other side of the sample.
4. Two or more clamps are mounted pressing these other plates.
5. One of the two plates on one side is connected to the positive pole of the generator.
6. One of the two plates on the other side is connected to the negative pole of the generator.
7. The generator is turned on.

8. The voltage supplied by the generator is varied to observe the effect on the tows.

9. The temperature of the tows is measured.

13.3. Image

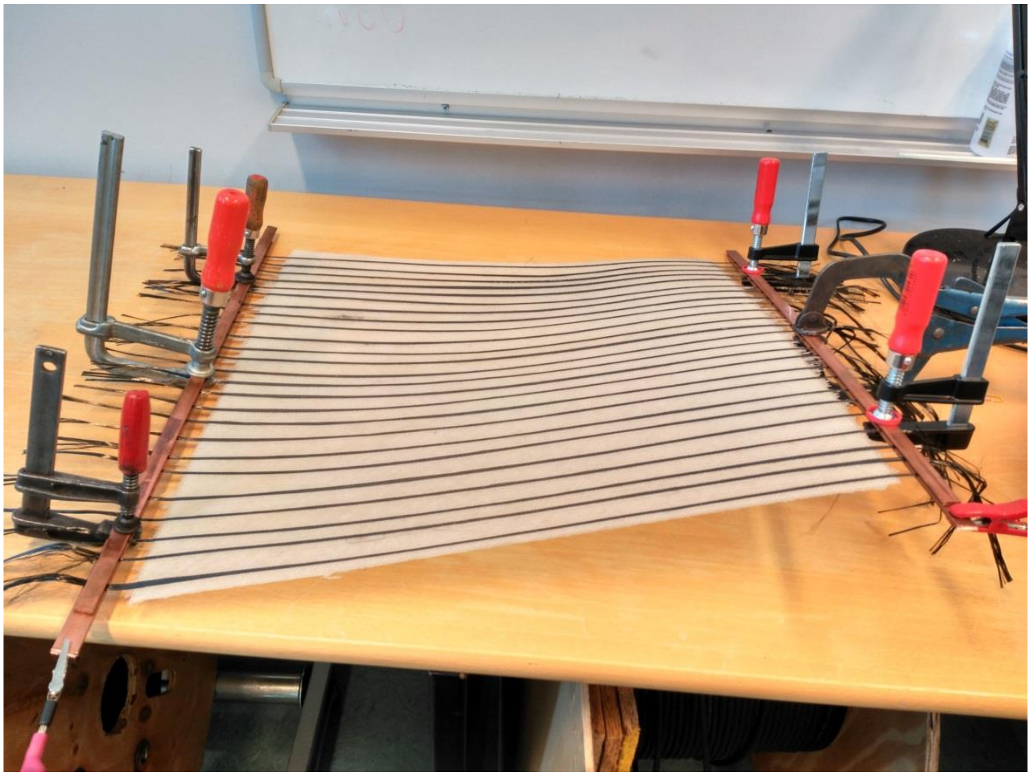

Figure 21. Image of the system

13.4. Results

The results of the experiment –voltage, intensity, and temperature values- are shown in the following table. The temperatures that are presented in Table 6 are the maximum temperatures measured in the sample. The minimum temperatures hardly vary. It was observed that there were some tows which were not affected by the current because of bad connection between the plates.

Table 6. Results of test 3: voltage, intensity, and temperature values.

DATA EXPERIMENT 14/04/2016 14:00		
Voltage (V)	Intensity (A)	Temperature (°C)
6,8	3,7	31
8,9	5,2	38
10,8	6,5	42
11,7	7,5	51
13,2	7,8	61
15,2	9,1	70
16,6	12,6	81
18,9	15,0	88
20,8	17,7	102
22,2	19,4	113
22,8	20,5	117
50 cm x 50 cm		

13.5. Conclusions

The main conclusion of this experiment is that it is hard to achieve a uniform temperature throughout all the tows. To be able to achieve a uniform temperature the pressure of the plates on the fibers should be adequate and the size of the tows should be the same.

PART 4: CONCLUSIONS

14. Results and discussion

In this project, it has been confirmed that carbon fiber reinforced polymer (CFRP) is a composite with properties that make it great choice in many engineering applications. It is due to its high mechanical properties together with light weight; thus, the consequence of using CFRP in the structural parts is that to achieve the same strength and stiffness less weight is needed, compared to the common metals.

The main disadvantage of using CFRP is the high cost of the manufacturing process. The manufacturing process of the carbon fibers and the manufacturing process of the CFRP, which includes the curing and the molding process, imply different heat treatments. In order to study the heating of the CFRP by means of electricity the experiments have been performed.

It was already known that the carbon fibers are a conductor material. Obviously, this could be confirmed from the tests. In the first test it was discovered that the behavior of the carbon fibers when they conduct electricity is similar to that of semiconductor materials. On the condition that carbon fibers conduct electricity their temperature increases, and with the increase of the temperature the resistance of carbon fibers decrease, unlike metals.

In the other experiments, it was possible to heat up the carbon fibers up to the desired temperature of 115°C. However, this temperature was not uniform on the whole carbon fiber tow in one of the tests, and not uniform on the surface on the other test. Therefore, it was not possible to heat the carbon fiber tows in an adequate way.

The fact that the carbon fiber tows could not be heated in an adequate way might be caused because of the equipment used. Actually, when heating one carbon fiber tow it burned in the point of connection. In addition, having it on a table might have affected the temperature the tow. Another point to take into account is the accuracy of the infrared thermometers.

In the third test where an area was intended to be heated the temperature was again no uniform. In this case, it was observed that the connection with the plates was not good enough and some carbon fiber tows where not conducting at all.

15. Challenges during the tests

The performance of the experiments has been highly affected by some factors that have not allowed for reaching the desired objective. This was to determine the suitability of heating the CFRP by means of conducting electricity through the fibers. The current stage of the tests does still need further development in order to achieve a result that showed whether this method is suitable or not. The main difficulties that were found during the tests are explained hereunder.

Test 1, as explained above, was mainly carried out as a first approach to the behavior of the CFRP when connected to a generator to heat it up. The first thought was to start by heating one of the fabrics. However, there was not enough knowledge on how the filaments would perform and, in addition, the actual voltage that would be needed it. Therefore, the way to perform this experiment was heating up a single tow.

Each extreme of the tow was connected to an electrical spice connector. These were then connected to the generator by means of cables. The carbon fiber filament laid on a table during the experiment. The first issue that was encountered in this case was that the joint and the electrical spice connector started to heat up too much. Actually, up to the point where it started to melt. This fact together with the fact that the tow was on a wooden table which could influence the temperature of the tow were the main limitations in this test.

Test 2 was performed the same way but measuring the temperature, as explained in the respective section. In this case, the temperature was controlled and the tow was heated up until the temperature needed in the curing and molding was reached. At this temperature the electrical spice connectors did heat but did not melt. Nonetheless, another issue was encountered.

In order to measure the temperature, an infrared thermometer was used. The way this type of thermometers work is by measuring the thermal radiation emitted by an object. These thermometers detect the radiation emitted from an area. The area of the carbon fiber is very small compared to that that the infrared thermometer may detect. Therefore, the accuracy of the measures is to be questioned. Furthermore, the temperature of the tow was far from being uniform.

In test 1, test 2, and test 3, the carbon fiber fabrics were not used. The reason is that it was not possible to connect them to the generator. In addition, the fact that the tows were in contact could imply having a short circuit. In that regard, Baltic Yachts supplied the other two samples with the separate tows and four metal plates.

In test 3 the sample with the tows in only one direction was used, shown in Figure 19. This was connected with two plates in each side pressing together the tows. The reason why the other sample, shown in Figure 20, was not used is that there were not enough plates and, in addition, in this case a short circuit could also be produced. The main problem that was encountered in this test is that the temperature of the carbon fiber tows was far from being uniform. Actually, the results in this case were much worse than that of test 2. The non-uniformity can be attributed to the bad connection of the tow with the metal plates, even if three clamps in each side were used. Moreover, in this case the point of connection of the cable with the metal plates reached high temperatures and the isolating cover started to melt. On the other hand, the material holding the tows together did not seem to heat much.

Hence, development of the thesis was limited by the equipment of the laboratory since it is by far not that that could be found in a specialized company in this sector. And last but not least, the time was a determining factor.

16. Further work

The current results of the project do not match the desired objective; thus it can be continued. The way to continue should imply to take into account the current limitations and try to overcome them. The most important point is to solve the non-uniformity of the temperature.

The heating of a single carbon fiber tow could be done without having it lying on a table but being on the air. In addition, the points of connection should be improved in order to avoid them to heat up too much. These improvements might make the temperature more uniform. Moreover, the temperature should be measured in a more accurate way; thus, instead of using an infrared thermometer, some kind of sensors measuring the temperature at different points could be used.

Furthermore, this test could be done some more times in order to find a correlation between the length of the tows and the voltage that is needed to reach the desired temperature. This relation is the most probable to be linear. The voltage needed to heat up carbon fiber tows that are in a parallel circuit should be the same than to heat up a single carbon fiber tow of the same length. The reason is that the voltage at the extremes of resistances in parallel is the same and the total current is the sum of the current passing through each resistance.

The previous results would be used to calculate the voltage needed to heat up the parallel carbon fiber tows in the sample with separated tows in only one direction. Moreover, the issue to solve in this case is the connection between the tows and the metal plates. The plates used in the test were scant flexible, and therefore despite using clamps the tows were not well pressed. In that regard, using more flexible metal plates could be tried so to check if in that case the connections were better. In case they were, the uniformity of the temperature is probable to be improved. Moreover, it should be verified that the temperature of the resin also increases as desired. The temperature, again, could be measured using different sensors spread throughout the samples.

The next step could be to focus on bidirectional carbon fiber tows samples. To avoid the possible short circuit, the tows with different directions should not be in contact. The way to solve this issue could be to put resin in between. That is to say, to build the sample in two layers, one with the tows in one direction and the other with the tows in the other direction, with resin in between. Then, the four sides of the sample should be connected to a generator, producing the same voltage in both directions if the sample is quadratic. If this experiment is successfully performed, it could be made more complicated by adding layers at -45°, and later at 45°.

If all the previous steps were successful, the progress in comparison to the current stage of the project would be highly noticeable. Furthermore, the next steps would be to use fabrics. This should be heated up, and epoxy resin could be added to make the tests much more realistic. At the moment, it is difficult to predict how the process could turn out as during the development new issues could be encountered. Nevertheless, it would be satisfactory to have it continued.

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