Development of Wall Material for Shelters

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Abstract:

The idea of material safety and survival in the rough environments and critical situations is one of the central problems in manufacturing. What are the best options available in designing a material that would be impact resistant, durable and be able to act as a shock absorber? How should specific physical and mechanical properties of such a material be combined to manufacture a box or container for shelter or other essential survival products, which would remain intact even in very brutal environments? The aim of the research part of this work was to determine whether the thickness of the impact absorber material (foam) with the sandwich structure affects the whole structure, especially the one made of the honeycomb material. In addition, the minimum foam thickness, necessary for the structure to maintain its optimal rigidity and strength against impact stresses, was calculated. To achieve this goal, three sandwich structures with the same primary material but different foam thickness was designed and manufactured and then measured to determine and evaluate the impact strength to the core of the construction. Besides, a compression test was performed during the experiment with the help of the tensile testing machine. The values obtained from the test were tabulated, and the results were compared with each other.

Keywords:	Composite, Reinforcement, Fiber, Material strength, Impact strength, Impact absorber
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Idén med material säkerhet och överlevnad i extrema miljöer där konstruktionen utsätts för stora yttre krafter som t.ex. stormar, jordnävningar och meteoritnedslag är ett av de centrala problem inom material tillverkning. Vilka är de bästa alternativ som finns att utforma ett material som är slagtåligt, hållbart och samtidigt fungera som en stötdämpare? Hur bör särskilda fysiskaliska och mekaniska egenskaper hos ett sådant material kombineras för att tillverka en låda eller en skyddskonstruktion för överlevnad. Syftet med arbetet var att ta reda på om tjockleken på ett stötdämpande komposite material (skum) i en sandwichkonstruktion påverkar hela strukturens hållfasthet. Dessutom beräknades minsta tjocklek på det stötdämpande materialet i väggen för att materialet skall behålla sin optimala styvhet och styrka efter stöt. För att uppnå detta mål, utformades och tillverkades tre sandwichstrukturer med samma primära material men olika skum tjocklek varefter dessa strukturer testades för att bestämma och utvärdera konsekvenserna av en stöt mot materialet. Med hjälp av dragprovingsmaskin utfördes ett kompressionstest och de värden som erhölls vid testet jämfördes med varandra.

Nyckelord:	Komposit, Fiber, Fållfasthet, Slagtålighet, Stötdämpare
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1. INTRODUCTION

The idea of material safety and survival in rough environments and critical situations is one of the central problems in manufacturing. What are the best options available in designing a material that would be impact resistant, durable and be able to act as a shock absorber? How should specific physical and mechanical properties of such a material be combined to manufacture a box or container for food, shelter or other essential survival products, which would remain intact even in very brutal environments? These are the questions that are strived to be answered in the course of this thesis.

To design and construct a product, different conventional materials can be used, for example the most common materials are metal, wood, ceramics and polymers. All the mentioned materials have their own beneficial physical properties; however, none of these materials alone can offer multiple properties at the same time. Metals are strong but they are too heavy, therefore they cannot be used in all applications. Wood is relatively soft. Ceramics are very brittle, and polymers yield to constant and intensive tensile force. All these materials can be replaced with composite material, which would combine all their beneficial properties and be many times lighter and stronger.

Composite materials are produced by mixing or combining two or more external materials into one final material, to achieve an unique and durable property with combination of different properties. Composites or fiber-reinforced materials differ from other thermoplastics and thermosetting plastics in the way that the consistent components used in the reinforced material have different molecular structure and are mechanically separable as shown in Figure 1.1. When components are set as one in a bulk form, the consistent materials work together and they will keep their original form and make the final properties in the composite material more durable and stable. The reinforced materials properties will be more reliable than every separate individual component used in it.

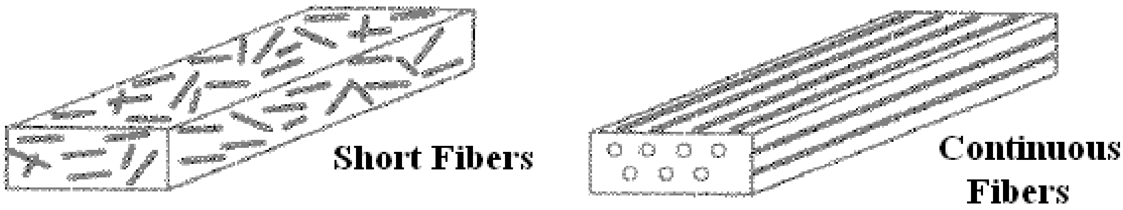

Figure 1.1 Two different kinds of fiber placement in composite material
Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, Composites manufacturing : materials, product, and process engineering, pp. 245

The target topics of this thesis are composite materials, such as honeycomb, preimpregnated and foam sandwich, and their features. Composite materials are used for manufacturing parts with relatively low weight and small volume, which at the same time give the structure additional rigidity and strength compared to if the structure was made of one single material.

In the theoretical part of the thesis, first, mechanical and physical properties of different types of compositions are explored and compared with various types of reinforcements and matrices used in a composite material. Secondly, manufacturing of reinforcements and the method of their applications are described. Finally, manufacturing and application methods for the aforementioned materials are introduced, analyzed and compared.

This has been the scope of this thesis research, which is going to be written to serve the primary aim of the work – exploration of the impact-resisting properties of composite materials and designing of the optimal material structure for the rough environments.

2. OBJECTIVE

The objective of the research is to determine whether the thickness of the impact absorber material (foam) with the sandwich structure affects the whole structure, especially the one made of the honeycomb material. In addition, to calculate the minimum foam thickness, necessary for the structure to maintain its optimal rigidity and strength against impact stresses. To achieve the result and a visual inspection, a compression test will be performed during the experiment with the help of the tensile testing machine. The values obtained from the test will be tabulated, and the results will be compared with each other.

2.1. Shelter

Tents are often used in humanitarian emergencies, such as war and earthquakes. At times, however, these temporary shelters become a permanent or semi-permanent home, especially for displaced people living in refugee camps or victims of a nature disaster who can't return to their former home and for whom no replacement homes are made available. The stresses on a shelter are mostly from objects colliding with the walls or falling objects on the top of its roof.

2.2. Simulation of Shelter Wall

I order to make the traditional shelters more secure and steady against external forces which are the main objective for this research, a composite material is replacing the fabric on covering the shelters to test its rigidity and toughness for measuring and determining the maximum safety the walls can provide the shelter and the user.

3. INTRODUCTION TO COMPOSITE MATERIAL

The composite material concept is found in the nature. Wood can be given as an example, which is a made of cellulose fibers matrix mixed with nature glue called lignin. The shells of invertebrates are another example for composite, such as snails and oysters. These shells are much stronger then advanced composites made by humans. According to scientists, fibers taken from spider webs are many times stronger than synthetic fibers. Examples of conventional composites are mixture of sawdust together with clay which makes particulate composite and mixing straws in clay will produce short fiber composite. The core concept for reinforced material is that it is made of matrix material. Usually, composite material is produced in the way that fibers are mixed in a matrix resin. Different shapes of reinforcements can be used in a composite material, like fibers, particulates, whiskers, and for matrix material polymers, ceramics and metals can be used. The fibers in the matrix can be of different shapes and lengths like short, long or continuous. Every configuration results a special property for the final material. The main point with the composite material is that, the fibers caries the load on the material and it is stronger along the axis of the fibers in the composite material. Long continues and unidirectional (UD) fibers with a certain load applied, only the fiber alone caries more load then the matrix itself. Short fibers of same material will yield to the load applied and it will relay on the matrix. The fiber form is selected depending on the kind of application and manufacturing method. Long fiber reinforcements are used in structural applications for its toleration toward heavy loads, but in the case of non-structural applications, short fiber reinforcements will fit just fine. In Compression and injection molding of composites short fibers are used for better result, but in filament winding, pultrusion and roll wrapping continuous fibers are used. Composites provide the advantages of lower weight, greater strength and higher stiffness. Figure 3.1 shows the physical properties and classifications of different materials due to their weight and strength. As Figure 3.1 shows, the density for composite materials stands between metals and wood, but in tensile strength and tensile modulus it competes with metals.

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, *Composites manufacturing : materials, product, and process engineering*, pp. 23-28

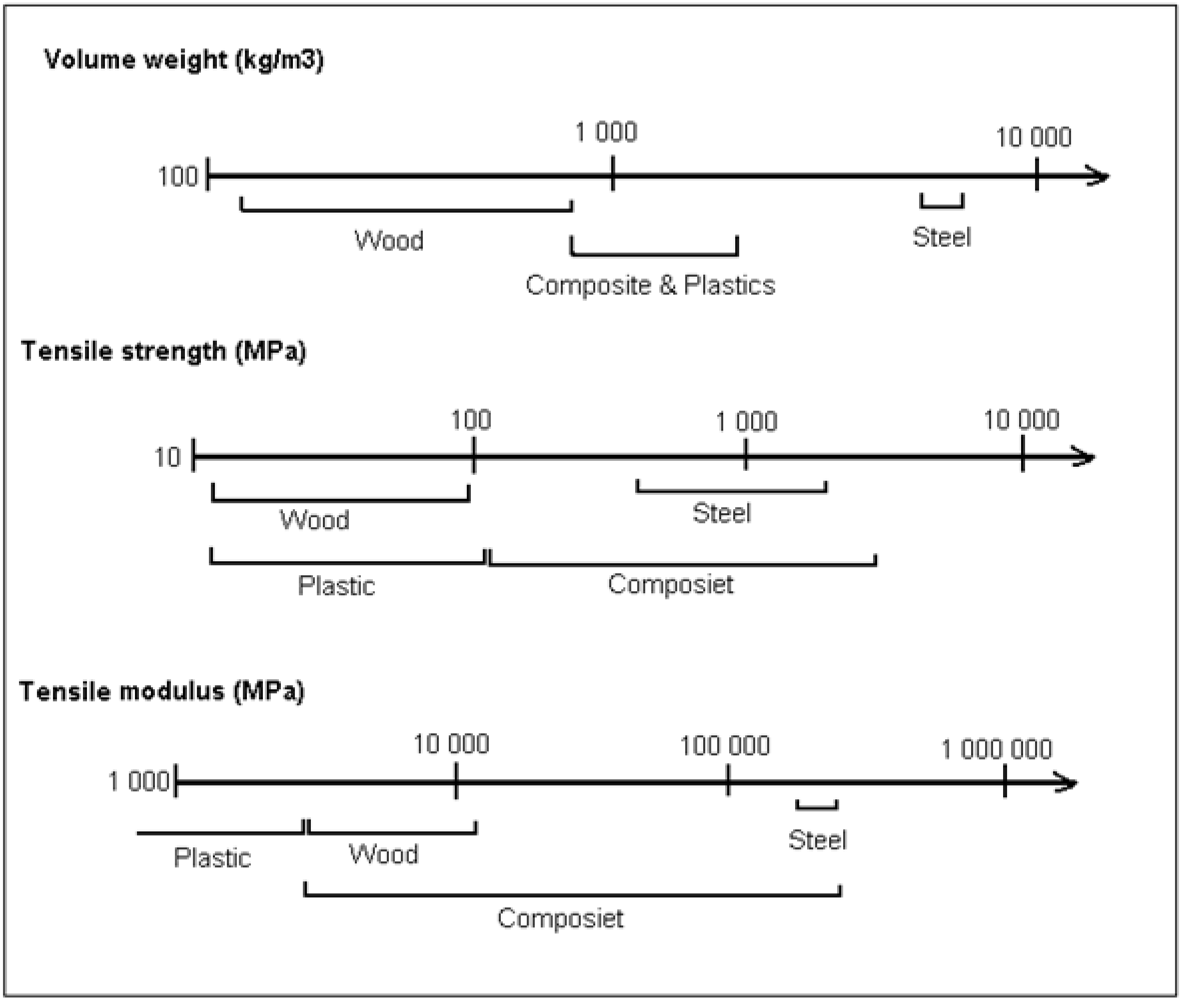

Figure 3.1. Comparison of physical properties and classifications of different materials.

Authors own work

4. Requirements for Selecting Engineering Materials

In the planning stage, the important question is that how do we decide the correct material for a particular application. Material selection is an easy concept but it requires a knowledge and awareness in behaviour and performance for the material used in the process. The most important first step in design and processing is to research and clearly identify the purpose and the service environment in which the proposed product will be used in, then the candidate materials are selected for the application. The following is regarded as the most important material characteristics requiring consideration for most engineering components:

1. Mechanical properties - strength, stiffness, specific strength and stiffness, fatigue and toughness, and the influence of high or low temperatures on these properties.
2. Corrosion susceptibility and degradation.
3. Wear resistance and frictional properties.
4. Special properties, for example, thermal, electrical, optical and magnetic properties, damping capacity, etc.
5. Molding and/or other methods of fabrication.
6. Total costs attributable to the selected material and manufacturing route.

4.1. Mechanical Properties of Polymers

Mechanical properties are mainly about **Stiffness** and **Strength** of the material. When a stress is applied, the material responds by exhibit a viscous flow through the material (which dissipates energy) and by elastic displacement (which stores energy). The mechanical properties for viscoelastic materials are dependent on time, temperature and strain. However, the conventional tests on stress-strain are regularly used to explain the short-term mechanical properties of plastics. It is not relevant to use the same information on one plastic category for every existing plastic material. To provide design data for different plastics, a long-term test is necessary. The effect of temperature on material is illustrated in Figure 4.1. When temperature is increased the plastic material becomes more flexible and for a specific stress the material deforms more. Another important aspect of plastic behaviour is the strain rate effect in Figure 4.2. If the thermoplastic is subjected to a rapid change in strain it will react stiffer than the same maximum strain at a slower rate.

R.J. Crowford, 1998, Linacre House. Jordan Hill, Oxford OX2 8DP 225 Wildwood Avenue, Woburn, MA 01801-2041, *Plastic Engineering* – 3rd ed. pp.18-26

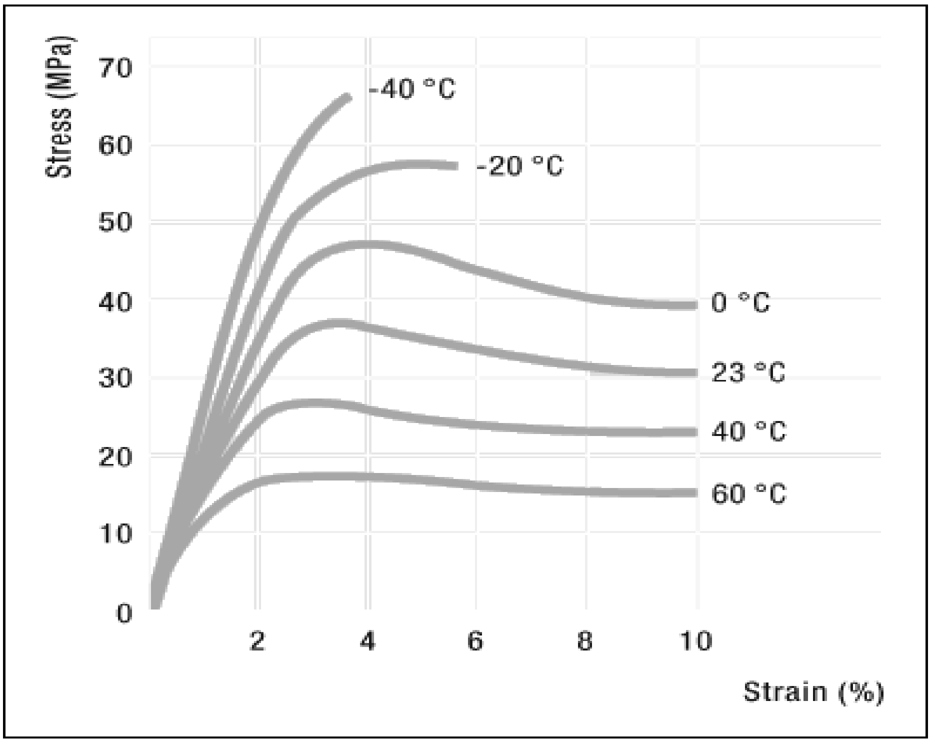

Figure 4.1. Stress-strain to temperature

http://www.springerimages.com/Images/RSS/1-10.1007_s11661-008-9514-5-5

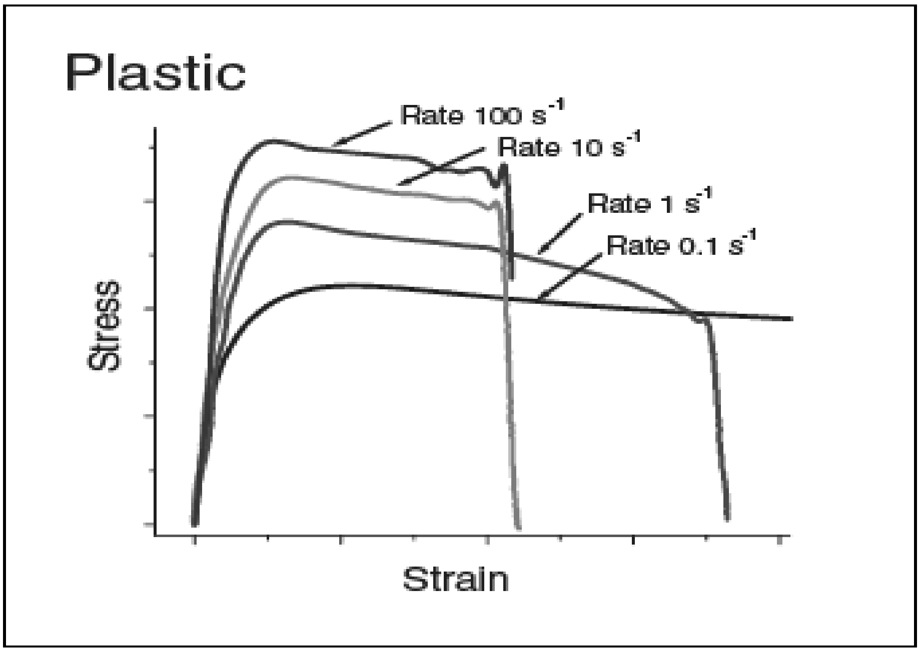

Figure 4.2. Effect of strain rate on stress-strain behavior of same plastic part.

http://www.globalspec.com/RefArticleImages/8DE033B4047F3F210EE55EDEB387249B_D1_D1_17.gif

4.2. Function of Fibers and Matrix

By reinforcing plastic together with fibers, either with chemical or physical methods, it results a composite material as a final product. In order to get a good understanding of composite materials behavior, it is essential to have a good knowledge of the role of fibers and matrix in composite. Here, the most important roles and functions of fibers and matrix materials are discussed.

The main functions of the fibers in composites are:

- To carry the load. In a composite structure, 70% to 90% of the load is carried by the fibers.
- To give stiffness, strength, thermal stability and other core properties in the composite.
- To provide electrical conductivity or insulation, depending on the type of the fiber used in the composite structure.

The matrix in the material gives several different functions to the composite structure, most of which are the important factors to the satisfactory performance of the structure. Fibers in themselves and applied alone in a structure are of very little use with the absence of matrix or binder materials.

The important task of a matrix material includes the following:

- The matrix material works as a binder of the fibers together in the material and transfers the applied load to the fibers. It gives rigidity and shape to the fibers.
- It works as an isolator for the fibres so that individual fibers can act separately. This stops or slows the propagation of a crack.
- The matrix material provides protection and works as shield for the reinforcing fibers against chemical attack and mechanical damage.
- Vary much depending on the matrix material selected for the application, the performance characteristics such as ductility, impact strength and other mechanical properties are influenced. A ductile matrix increases the toughness of the composite structure. In order to achieve higher toughness in the structure, thermoplastic-based composites are selected.

- The type of matrix material as well as its compatibility with the fiber used with it as an important factor for failure mode in the composite material.

M. H. Irfan, 1998, Published by Kluwer Academic Publishers, P.O. Box 17, 3300 AA Dordrecht, The Netherlands, *Chemistry and Technology of Thermosetting Polymers in Construction Applications*, pp. 8-23

5. MECHANICAL BEHAVIOR OF COMPOSITES

Composite materials have lot more mechanical behaviour characteristics than most of conventional engineering material. Some of these characteristics are simply modifications and combination of conventional behaviour of materials.

5.1. Types of Reinforcements

The fillers used as reinforcements usually are made from fibers of different materials but particles like for example glass spheres are also used. As reinforcing fibers a wide range of amorphous and crystalline materials can be used. These materials consist of glass, carbon, boron and silica etc. In the past few years fibers used in reinforced materials have been produced from synthetic polymers, for example Kevlar fibers made from aromatic polyamides and PET fibers. Figure 5.1 illustrates the stress strain behavior of some typical fibers used in composites and Table 5.2 represents the techniques for manufacturing of various types of composite materials. The raw materials used in composite manufacturing can be divided into two categories which are thermoplastics and thermosets. Glass used as a mixture in the form of fibers together with plastics for producing reinforced material, is a relatively inexpensive and is the principal form of reinforcement production. The glass fibers are produced by pultruding continuous strands of glass from an orifice, where the glass is melted by an electrically heated platinum crucible. One of the earliest successes in glass reinforcements contained a calcium-alumina borosilicate composition developed specifically for electrical insulation system called as (E-glass). Even though other glasses were developed afterwards in the application where electrical properties are not critical, but no commercial composition than E-glass is found. Some special glasses with higher strength and tougher mechanical properties are produced in small quantities for special applications e.g. aerospace technology. Fibers are produced and treated during production with an agent such as acrylic co-polymer which performs several functions and this treatment is called (sizing).

1. it makes the production of strands from individual fibers easier
2. it decrease damage to fibers during mechanical handling
3. it supports the fibers during molding process

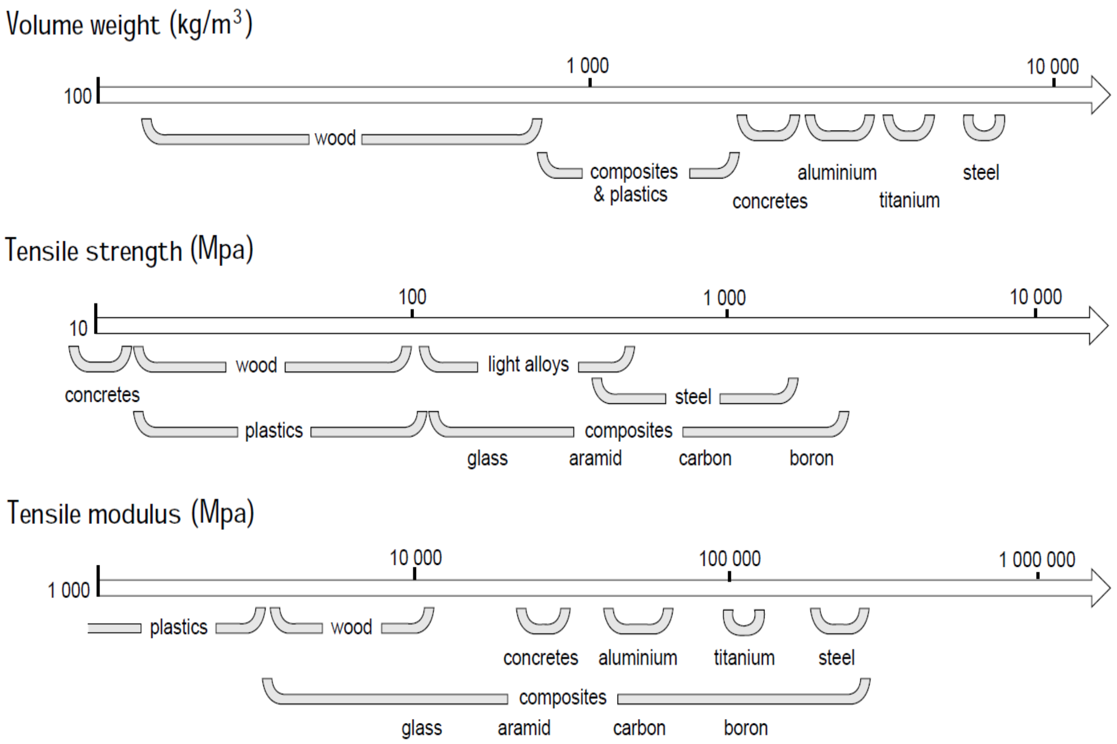

Figure 5.1. Different materials and their strength versus weight.

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 4,

http://www.formulaschools.com/curriculum/prepregtechnology.pdf

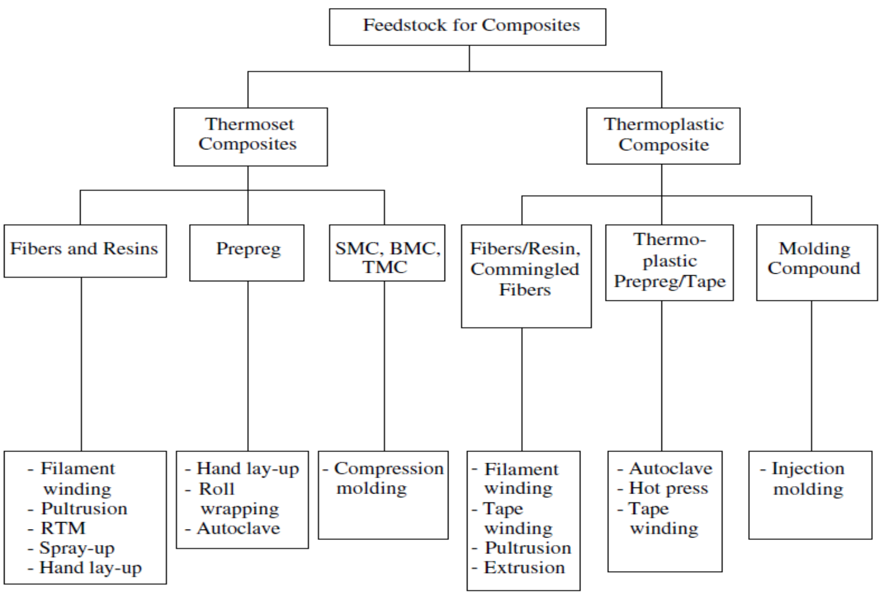

Figure 5.2. Classification of raw materials and methods for composite manufacturing

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, Composites manufacturing : materials, product, and process engineering, pp. 245

5.1.1 Reinforcements

Composite materials are made of reinforcement component which gives the important and the necessary stiffness and strength properties to the material. The structures of these reinforcements are thin rod-like shapes. The most common reinforcement materials are carbon, glass, aramid and boron fibers which have a fiber diameter range from 5µm up to 20µm. Due to this thin fiber diameters, it makes the processing and manufacturing relatively very flexible and easy. The fibers are usually made into strands for winding or weaving operations. The stiffness and strength in composite materials are provided by these fibers in the way that, the matrix makes the composite structure more rigged and transfers the load to fibers.

Fibers in composite materials can be produced in many different shapes and forms. The shapes can be from continuous to discontinuous fibers, long to short fibers, organic and inorganic fibers etc. Like said before the most widely and commonly used fiber materials in fiber-reinforced plastics (FRP) are carbon, glass, aramid, boron. The most economical fibers, glass are the most common one among all the mentioned fibers. The glass fibers are categorized into three different types: E-glass, S-glass and S2-glass. The physical properties of these glass fiber types are illustrated in Table 4.1. One of the most essential facts that the designer of composite material should pay extra attention to is the selection of right type of fibers for target application. The property of the final composite is totally dependent of the dimensions of chosen fibers. Figure 5.3 illustrates the of fiber form and its performance in the final product.

Table 5.1. Physical Properties of Fibers and Bulk Materials

Material	Diameter (µm)	Density (ρ) (g/cm³)	Tensile Modulus (E) (GPa)	Tensile Strength (σ) (GPa)	Specific Modulus (E/ρ)	Specific Strength	Melting Point (°C)	% Elongation at Break
Fibers								
E-glass	7	2.54	70	3.45	27	1.35	1540+	4.8
S-glass	15	2.50	86	4.50	34.5	1.8	1540+	5.7
Graphite, high modulus	7.5	1.9	400	1.8	200	0.9	>3500	1.5
Graphite, high strength	7.5	1.7	240	2.6	140	1.5	>3500	0.8
Boron	130	2.6	400	3.5	155	1.3	2300	—
Kevlar 29	12	1.45	80	2.8	55.5	1.9	500(D)	3.5
Kevlar 49	12	1.45	130	2.8	89.5	1.9	500(D)	2.5
Bulk materials								
Steel		7.8	208	0.34–2.1	27	0.04–0.27	1480	5–25
Aluminum alloys		2.7	69	0.14–0.62	26	0.05–0.23	600	8–16

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, Composites manufacturing : materials, product, and process engineering, pp. 245

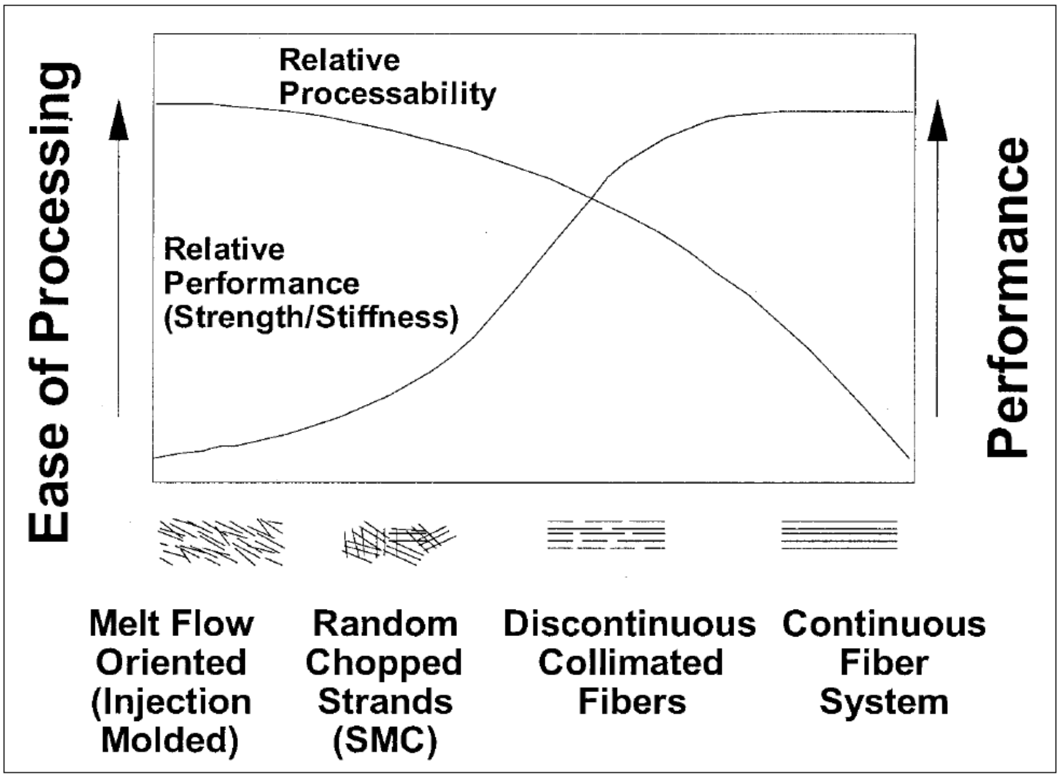

Figure 5.3. Graph over the role of fiber form on processing and performance.

Suresh G. Advani, E. Murat Sozer, 2003, Marcel Dekker, Inc. 270 Madison Avenue, New York, NY 10016, *Process Modelingin Composites Manufacturin, ch. 1.0*

5.1.2 Glass Fiber Manufacturing

Manufacturing of glass fiber plays a very big roll on the physical properties of the fibers. There are two types of Glass fiber materials in composite manufacturing: E-glass fiber and S-glass fiber. In order to produce other glass types with more or less the same ingredients but different physical properties, the amount of the raw materials and the processing parameters are adjusted to produce the required glass type, like S-glass. The raw materials are mixed carefully together and melted in oven at 1400˚C to 1700˚C, where then the melt flows into bushings containing hundreds of small orifices. Once the molten glass passes trough the orifices, glass filaments are formed and in the end it goes through a quench area where the filaments are cooled rapidly by water or air to below their glass transition temperature (T_g). In polymers the glass transition temperature, T_g, is often expressed as the temperature at which an amorphous solid becomes soft upon heating or brittle upon cooling.The amount of sizing used differs between 0.25% up to 6% of the original glass fiber weight. With the method of sizing the filaments gets several qualities which makes them easier in the stage of processing, including easier fiber wetting and processing, provides better resin and fiber bounding, and protects the fibers during handling and processing stage and works as a shield for them not to brake.

5.1.3. Carbon Fiber Manufacturing

Production of carbon and graphite fibers is based on PAN-material or pitch-based precursors. The precursors go through a series of operations during the productions. In the first stage, the precursors are oxidized by letting it go through extremely high temperatures. In the second stage, the precursor is treated with chemicals that give high stiffness-to-weight and strength to weight properties to the pre-material. After surface treatment and sizing stage the material has improved its resin compatibility and handle ability.

PAN refers to Polyacrylonitrile, a polymeric fiber material with textile basis. Figure 5.4 shows the monomer for polyacrylonitrile. Pitch fiber is achieved by spinning purified petroleum or coal-tar pitch. Production of carbon fiber is mainly based on PAN-based fibers. Pitch-based materials are known to be more brittle and stiffer comparing to other polymeric materials due to their molecular structure composition. The weight of PAN during oxidation and carbonization reduces to 50% of its original weight. The production process of carbon fiber is very slow and because of the time and energy-consuming process relatively more expensive. Pitch-based carbon fibers and PAN-based fibers are produces in similar ways, but pitch is more difficult to spin and the resulting fiber is more difficult to handle.

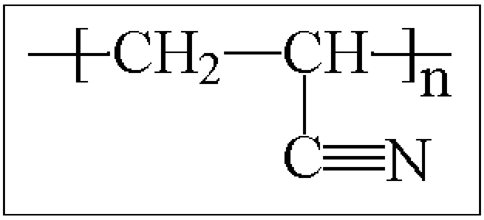

Figure 5.4. Polyacrylonitrile monomer

http://pslc.ws/macrog/kidsmac/polyac.htm

5.1.4. Aramid Fiber Manufacturing

Aramid fibers are known as the strongest and most durable material with the highest tensile-to-weight ratio among reinforced fibers. Because of their molecular structure, they provide good impact strength. Similar to carbon fiber, aramid fibers provide a negative coefficient of thermal expansion. Aramid fibers are very difficult to cut and machine and that is one of the prime disadvantages of processing this material. Production of aramid fibers are performed by extruding an acid solution, (a proprietary polycondensation product of terephthaloyl chloride ($C_8H_4Cl_2O_2$) and *p*-phenylenediamine ($C_6H_8N_2$) both contains an aromatic ring in their monomer and both are used to achieve Kevlar) through a spinneret. Through a drawing operation, aramid molecules are highly oriented in the longitudinal direction, and gain their enormous tensile strength. Figure 5.5 is a Aramid structure.
Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, *Composites manufacturing : materials, product, and process engineering*, ch.2.

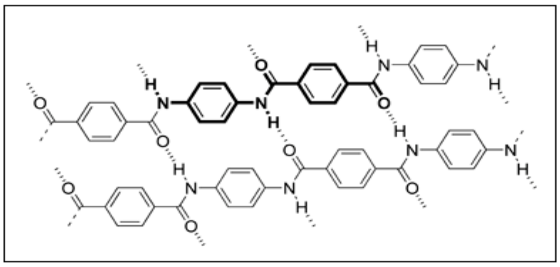

Figure 5.5. Aramid structure
http://www.edinformatics.com/inventions_inventors/kevlar.htm

5.2. Types of Matrix

Composites are made of matrix materials and reinforced fibers. Matrix material surrounds the fibers and consequently protects the fibers against chemicals and environmental attack. The matrix material in the reinforcement must have a lower modulus and a greater elongation than the reinforcement for the fibers to be able to carry maximum load. Reinforced plastic material used as matrix may be either thermosetting or thermoplastic. Figure 5.2 explains the role of matrix and the purpose of them.

Table 5.2. Role and purpose of matrix

CURING THE MATRIX (under temperature and pressure)	ROLE OF THE DIFFERENT CONSTITUENTS OF A MATRIX
Pre-polymers (with free reactive sites)	Hardener
Cure (joining of reactive sites)	Accelerator
Cured polymer	Fillers and Thermoplastic resins

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 8,
http://www.formulaschools.com/curriculum/prepregtechnology.pdf

5.3. Thermoset Resins

In the earlier days almost all thermosetting molding materials were made of composites in which it contained fillers such as wood flour, mica (a group of silica), cellulose, etc. to increase their mechanical strength. These types of materials were not generally considered as reinforced material for the reason that they did not contain fibers. Nowadays, the major thermosetting resins such as unsaturated polyester resins and to some extent epoxy resins are used as a composition with glass fiber reinforcements. The greatest advantage that these thermosetting materials can offer is that they don't evaporate rapidly during cross-linking process and they can be molded in room temperature at low pressure. Thermoset materials cannot be remelted or reformed after curing process. While curing, there will be tree-dimensional molecular chain formation between the monomers. Because of this cross-linking phenomenon, the molecules in the chain are not flexible and cannot move freely, and that's what makes the material very stiff and impossible to remelting and reforming. The material will be more rigid and thermally stable with higher number of cross-linking. Since the cross-linking density in rubbers and elastomers are much less, there for they become much more flexible. At high temperatures, thermosets can soften to some degree. This characteristic is used to create curves and bends in tube structure manufacturing, such as filament-wound tubes. Thermosets are always used with some form of filler or reinforcement since in general they are very brittle in nature. Thermoset resins are used at room temperature and that provides easy processability and better fiber migrations once used in various processes such as filament winding, pultrusion and RTM (Resin Transfer Molding). Thermosets offer a wide range of properties including thermal and dimensional stability, better rigidity, and higher electrical, chemical and solvent resistance. The most common resin materials used in composite material with thermoset quality are for example epoxy, polyester, phenolics, vinylesters, polyurethane and polyamides. Some of the properties of different selected thermoset resins are shown in Table 5.3.

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, *Composites manufacturing : materials, product, and process engineering*, ch.2.3

Table 5.3. Properties of Thermoset Resins

Typical Unfilled Thermosetting Resin Properties

Resin Material	Density (g/cm^3)	Tensile Modulus GPa (10^6 psi)	Tensile Strength MPa (10^3 psi)
Epoxy	1.2–1.4	2.5–5.0 (0.36–0.72)	50–110 (7.2–16)
Phenolic	1.2–1.4	2.7–4.1 (0.4–0.6)	35–60 (5–9)
Polyester	1.1–1.4	1.6–4.1 (0.23–0.6)	35–95 (5.0–13.8)

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, Composites manufacturing : materials, product, and process engineering, pp. 270

5.4. Epoxy

Epoxy is a material with a versatile resin system, and has a wide range of multipurpose ability which can be used in different processing purposes. Epoxy offers a low shrinkage rate of 0.01% and an excellent support to a variety of substrate materials. This resin is the most widely used material and it is used in many different applications from aerospace industry to sport products. For different applications there are special epoxy qualities with varying levels of performance to meet the applications need. To get a specific property for epoxy in an application, e.g. to modify the cure rate, to change the processing temperature, to adjust the cycle time, to change the toughness, to improve the temperature resistance of the material, can easily be done by changing the formulation of the epoxy mixture in the composite. To cure epoxy, a chemical reaction is needed with amines, phenols, carboxylic acids and alcohols. Epoxy is a liquid resin including several epoxide groups, such as diglycidyl ether of bisphenol A (DGEBA). Figure 5.5 shows an epoxy monomer and located in a complete chain. While curing, DGEBA molecules shape a network among each other as shown in Figure 5.6, and form cross-link and create a three-dimensional structure and finally results a solid epoxy resin. By decide proper amount of hardeners or catalysts, the cure rates for the epoxy can easily be controlled. Each and every different hardener has its own characteristics and different properties to the resulting epoxy material. The rate of cure is proportional to the process cycle time and production volume rate; in other words, the higher the cure rate, then the processing time for every cycle will be lower and at the same time the production volume rate will get higher. Composite materials based on epoxy provide very good performance at room temperature as well as elevated temperatures. Common epoxies operating temperature range reaches 90˚C to 120˚C, and for some special epoxies the temperature range easily reaches 200˚C. In application with high-temperature and high-performance is used, the cost for production will increase, but they offer very good chemical and corrosion resistance. Epoxies come in different forms, for example liquid, solid and semi-solid forms. Liquid epoxies are mainly used in RTM processes, filament winding, pultrusion, hand lay-up and with various reinforcing fiber materials included e.g. glass, carbon, aramid and boron, etc. Semi-solid epoxies are used in prepreg when the production methods are vacuum bagging or autoclave processes.

Epoxies are generally brittle in nature, but to be used in special applications and fulfill the desired purpose, “super epoxies” or toughened epoxies are developed to combine the outstanding thermal properties of a thermoset simultaneously having the toughness of a thermoplastic. To make the super epoxies, there are mixtures of thermoplastics added in the epoxy resin by various processes.

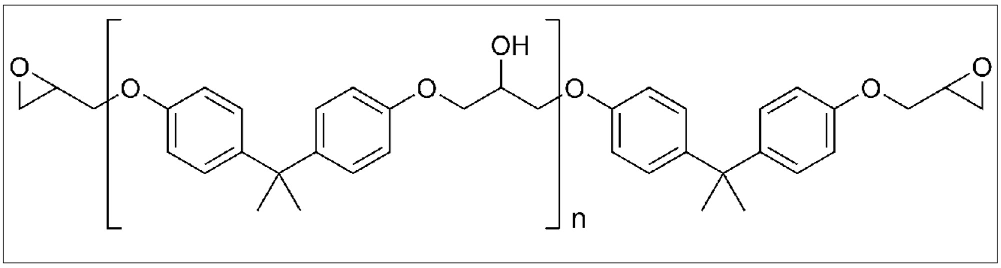

Figure 5.6. Epoxy monomer

http://www.chemtek.com.au/why-epoxy.htm

6. HONEYCOMB COMPOSITE

Honeycomb structure materials are mainly used in sandwich structures as cores between two thin high-strength facings. By using strong adhesives (phenol), honeycomb materials are joined together with facings in order to transfer the loads from one face to another, like shown in Figure 6.1. This material operates like a web of an I-beam, taking the shear loads simultaneously as providing its rigidity by keeping high strength materials away from the natural axis in the area where tension and compression stresses are highest. The difference between honeycomb sandwich structure and I-beam is that, the web is spread in the whole cross section of the sandwich structure and provides high tensional rigidity, whilst in the I-beam the web is in the centre of the beam, there for provides less torsion rigidity. This sandwich structure has the highest stiffness-to-weight ratio and strength-to-weight ratio. Figure 6.2 compares common aluminum, Nomex (aramid) and thermoplastic honeycomb.

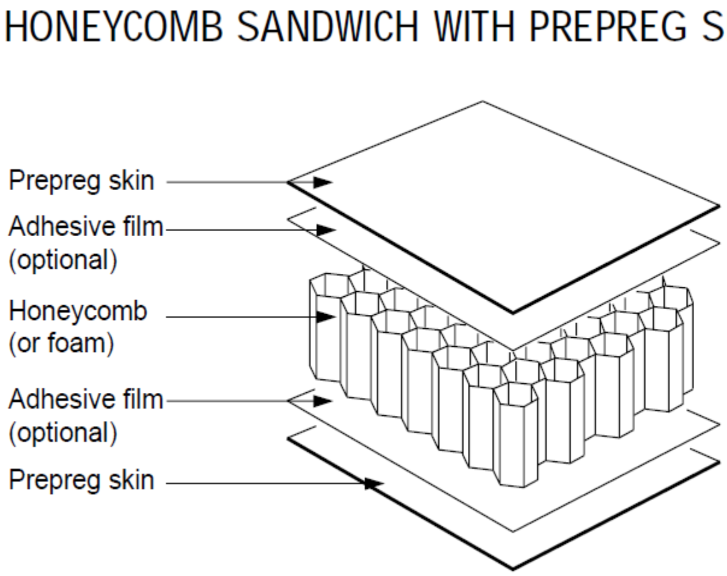

Figure 6.1. Honeycomb Composite

http://www.advanced-composites.co.uk/ Accesed:15.9.2009

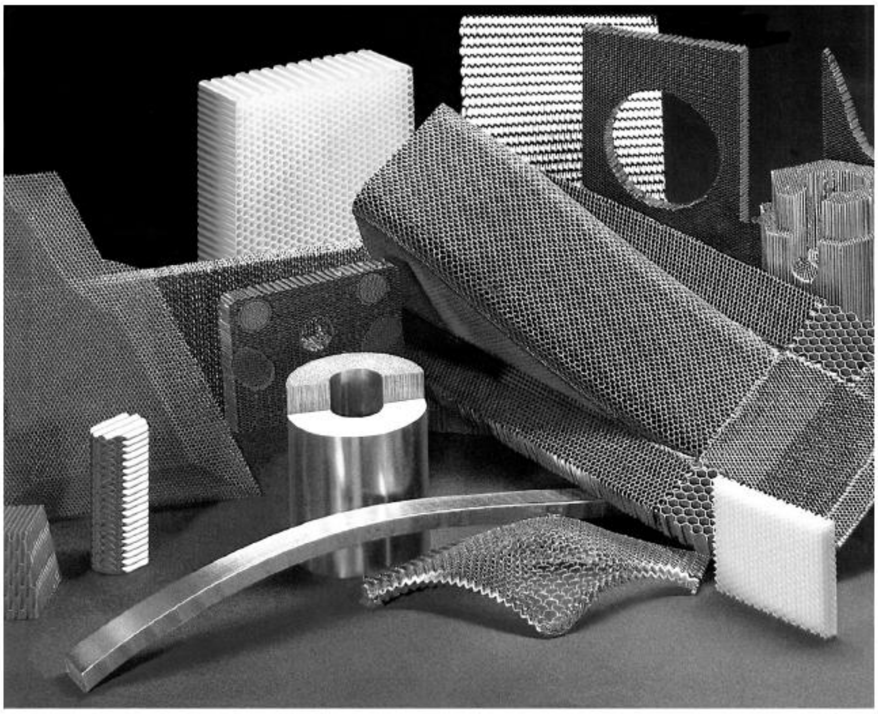

Figure 6.2. Aluminum, Nomex and thermoplastic honeycomb.
http://www.advanced-composites.co.uk

Honeycombs come in different shapes, but the most common honeycomb is the flat sheets type which is used as the core of the structure. The typical dimensions of the flat sheet honeycomb are 1.5 m x 2.5 m with a thickness of 3 mm up to 300 mm and the cell size for these common honeycombs are 3 mm to 25 mm in diameter. Usually the shape of the aluminum and the Nomex cells are hexagonal, whereas thermoplastic honeycombs have a circular cell shape.

Honeycomb materials, due to their strong mechanical characteristics they are used in aircrafts, transportations, marine industry, sporting goods, communications and many other industries. These constructions provide predictable crash behaviour and that’s why they are mainly used for the design of crash resistant parts. Honeycomb structures have the ability to operate as a radiation shield due to the angels and shape of the cells, and there for are used for the design of computer and communication rooms. The repetitive cellular structures works as a multitudinous waveguides, attenuating the transmitted signals across a wide frequency range. The physical properties of some selected honeycomb core materials are given in Table 6.1.

Table 6.1. Physical properties of some selected honeycomb core materials

Material	Cell Diameter (in.)	Density (lb/ft^3)	Max. Service Temp. (°F)	Stabilized Compressive Modulus (ksi)	Stabilized Compressive Strength (psi)
5052 Aluminum	0.125	8.1	350	350	1470
3003 Aluminum	0.5	2.5	350	40	165
Polvcarbonate	0.125	7.9	200	55	695
Aramid (Nomex)	0.125	8.0	350	80	1900
Glass-reinforced polyimide	0.1875	8.0	500	126	1300
Glass-reinforced phenolic	0.1875	5.5	350	95	940

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, Composites manufacturing : materials, product, and process engineering, pp. 366.

6.1. Properties of Sandwich Structure

Figure 6.3 illustrates the compensation and difference in properties for a solid material with honeycomb material. The comparison for honeycomb structure to I-beam is also introduced.

	Solid material	Core thickness t	Core thickness 3t
	t	2t	4t
Stiffness	1.0	7.0	37.0
Flexural strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

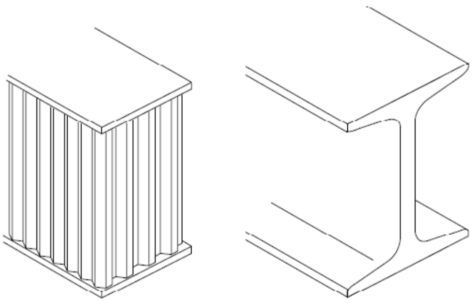

Figure 6.3. Honeycomb construction compared to I-beam

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 20, Accessed 10.3.2010

http://www.formulaschools.com/curriculum/prepregtechnology.pdf

6.2. Honeycomb Manufacturing

There are two main methods for honey core manufacturing. These two methods includes Expansion manufacturing and Corrugation manufacturing.

6.2.1. The Expansion Method

The expansion method is mainly used for manufacturing of aluminum and Nomex honeycomb composites. In this process, in stage one in order to prepare the initial material (for example Polypropylene), sheets of the material in use are stacked together in a block form. To obtain interrupted adhesive bonding between the sheets, stepwise adhesive node lines are printed on each sheet. This process takes place before stacking the material in one pile. After the stack of sheets is cured, the block is then cut into slices of correct thickness and expanded to achieve the desired cell size and shape. Figure 6.4 demonstrates the expansion honeycomb manufacturing process.

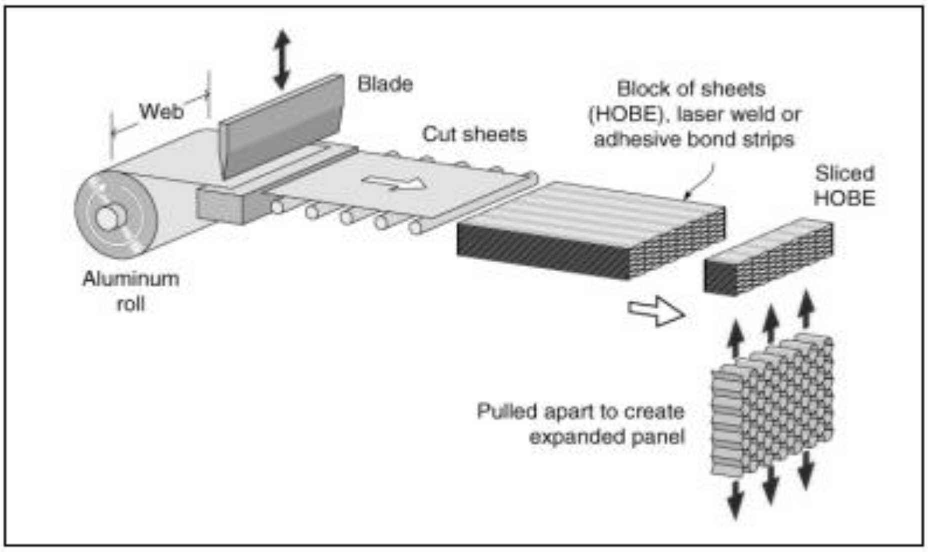

Figure 6.4. Expansion Honeycomb Manufacturing Method

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 20, Accessed 10.3.2010

http://www.hexcel.com/NR/rdonlyres/599A3453-316D-46D6-9AEE-C337D8B547CA/0/HexwebAttributesandProperties.pdf

6.2.2. The Corrugation Method

For this method in the first stage, corrugation rolls are used in order to transform the material into corrugation forms. The ready corrugated sheets are then stacked together, bonded and after they are cured the block is then cut in desired shape and size resulting honeycomb planes with no use of expansion. The corrugation manufacturing method is demonstrated in Figure 6.5.

Other core materials are also used as sandwich structures such as balsa wood, plywood and different foam core material. The shape, design and the structure of every cell gives the honeycomb structure different physical properties and it decides if the final structure is rigid, flexible or robbery. Foam materials applied in honeycombs are either thermoplastic resins or thermosetting resin processed by various techniques e.g. gas injection, blowing agent, expandable bead process. By using gas supplied agents to the resin, its density is decreased by forming closed or open gaseous cells in the honeycomb material. Foam is used to increase both the bending stiffness and the thickness of the structural members without changing or increasing the weight of the member.

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, *Composites manufacturing : materials, product, and process engineering*, ch.2.8

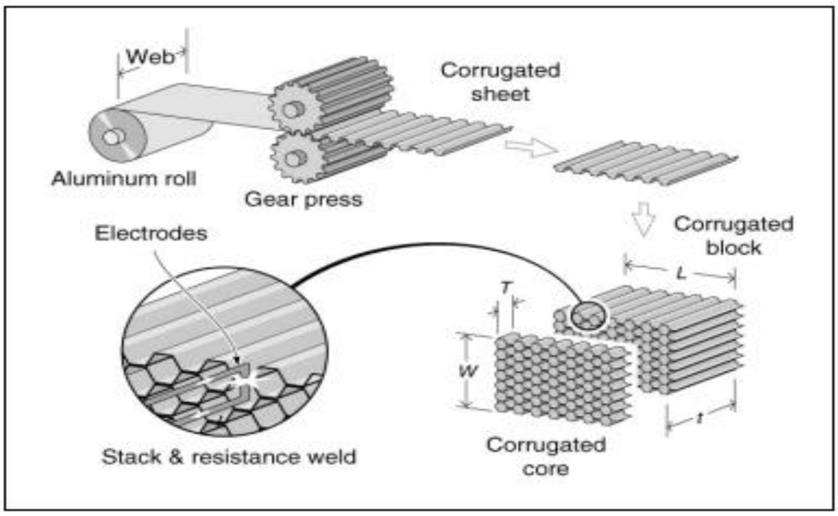

Figure 6.5. Corrugation Honeycomb Manufacturing Method
http://www.hexcel.com/NR/rdonlyres/599A3453-316D-46D6-9AEE-C337D8B547CA/0/HexwebAttributesandProperties.pdf

7. PREIMPREGNATIONS (PREPREG)

A prepreg consists of a combination of a matrix (or resin) and fiber reinforcement. It is ready to use for any component. Figure 7.1 prepreg availability in two forms:

- UNIDIRECTIONAL (UD)
- FABRIC

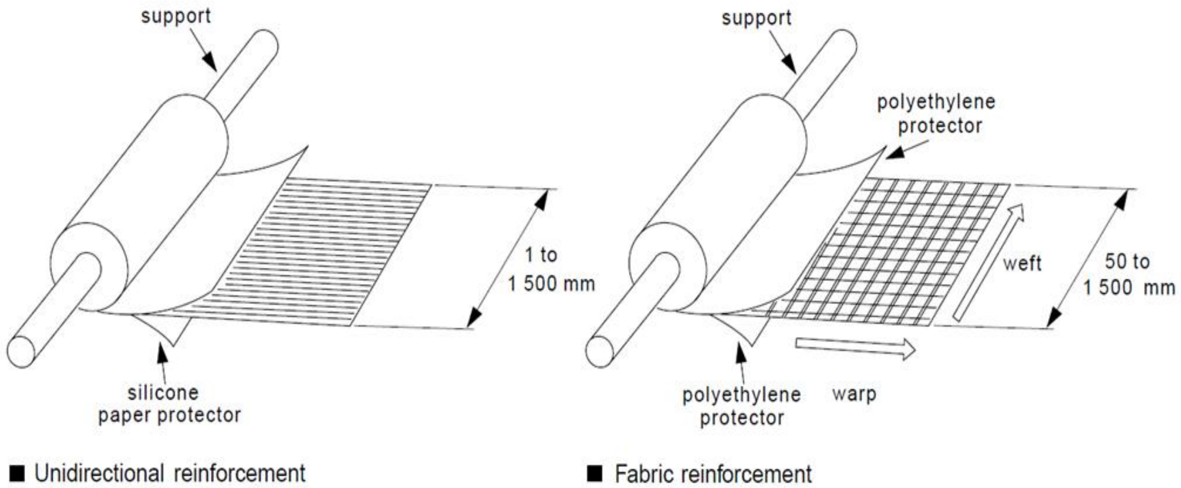

Figure 7.1. Types of preimpregnated material

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 4, Accessed 10.3.2010

http://www.formulaschools.com/curriculum/prepregtechnology.pdf

7.1. Prepreg Manufacturing Techniques

Figure 7.2 demonstrates industrial manufacturing methods of prepreg material. As shown i the schematic picture, the prepreg production can be performed with two techniques.

- Film transfer route (prepared in two steps)
- Solution route

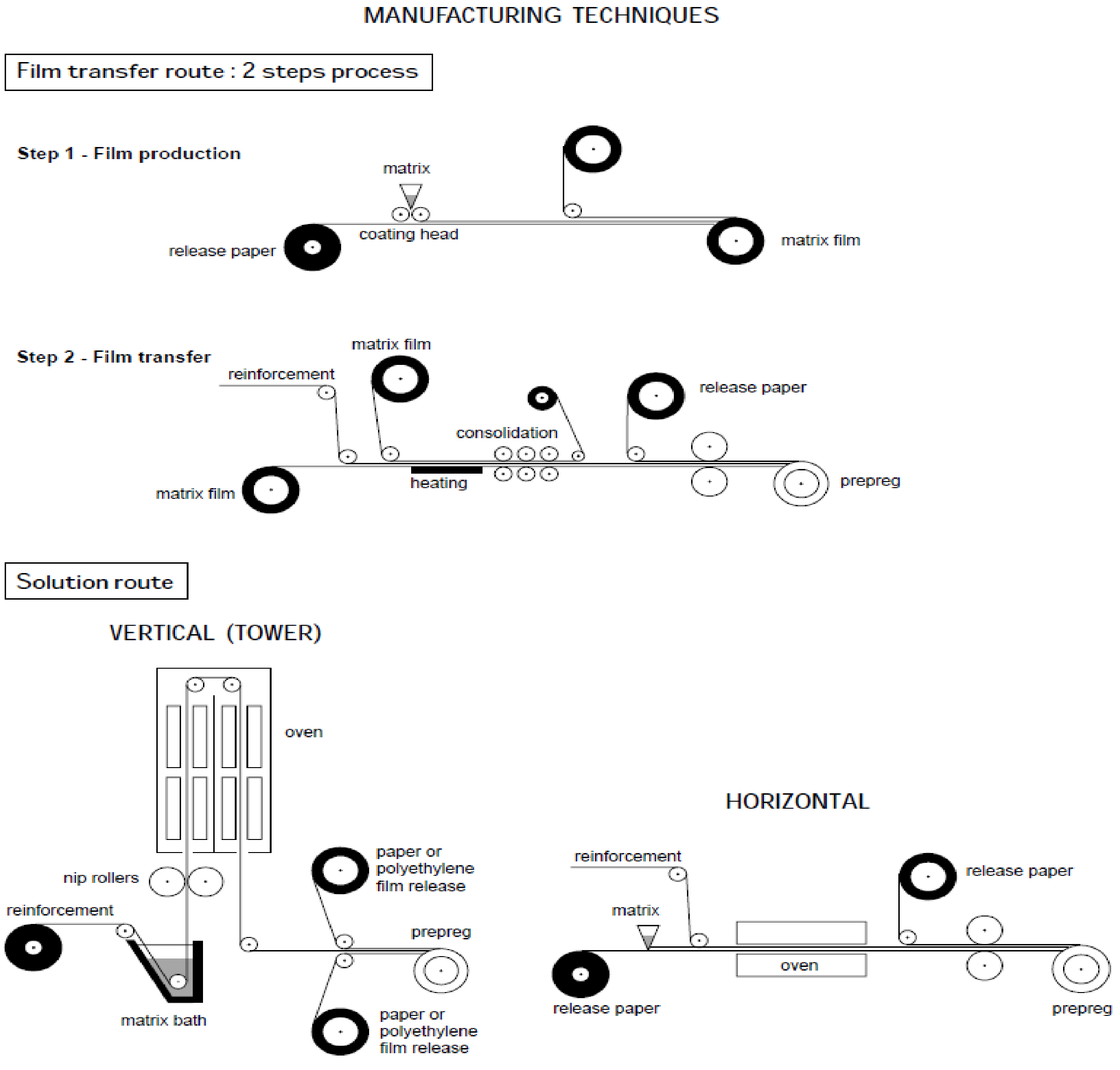

Figure 7.2. Prepreg manufacturing methods in two ways.

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 4, Accessed 10.3.2010

http://www.formulaschools.com/curriculum/prepregtechnology.pdf

8. DIMENSIONS AND FIBER REINFORCEMENT IN COMPOSITES

Fiber reinforcements used in composite structures usually have diameters varying from 7 µm to 100 µm. These fibers come in two forms, either continuous fibers or in the form of chopped strands with length of 3 mm – 50 mm. In manufacturing both of these fibers can be used as a mixture. There is an important parameter used relating manufacturing with fibers. In the case of manufacturing with chopped strands, the parameter is called Aspect Ratio and it is lengths to diameter ratio for the fibers in process. This parameter is mostly used for short-fiber composites and the properties of these fibers are very dependent on the aspect ratio. The grater the aspect ratio the grater will be the strength and stiffness of the composite structure.

8.1. Continuous Fiber Composites

In composite manufacturing, the greatest strength and stiffness is achieved when the structure is reinforced with unidirectional (UD) continuous fibers. The analysis of this system is relatively straightforward and obvious.

8.2. Reinforced Composites Deformation Behaviour

As it was mentioned in the earlier chapters, the physical properties of composites i.e. stiffness and strength properties, can be increased significantly by the addition of reinforcing fillers. A reinforced composite consist of two main core components; the matrix which can be either thermoplastic or thermosetting and inner reinforcing filler which comes in the form of fibers. Figure 8.1 shows the different forms of fibers which can be used as fiber reinforcements. The matrix its self has a low strength in comparison to the fibers or reinforcements used which is also stiffer and brittle. For the best result and maximum benefit by using the reinforcements, the fibers in the composite should carry as much stress applied to the structure as possible. The main function of the matrix is to support the fibers to keep their positions and transmit the external loading to them by shearing at the fiber/matrix interface. Since these two components are quite different from each other in structure and properties its convenient to consider them separately in manufacturing processes. In case of failure in matrix and fiber co-operation in the composite structure, the fibers cannot bear the maximum stress applied and the matrix do not have the ability to support the reinforcement material and results total deformation in the whole composite material and component.

R.J. Crowford, 1998, Linacre House. Jordan Hill, Oxford OX2 8DP 225 Wildwood Avenue, Woburn, MA 01801-2041, *Plastic Engineering* – 3rd ed. pp.171-184

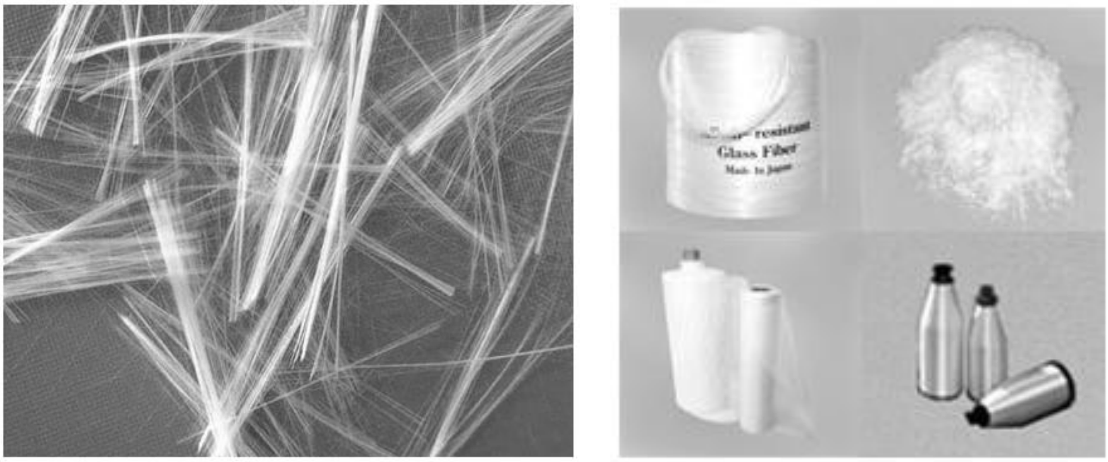

Figure 8.1. Different Forms of Fiber (above are pictures of fiber-glass in various forms)
http://www.allproducts.com/manufacture97/jedhappy/product5.html , Accessed: 6.10.2009

9. IMPACT BEHAVIOR

One of the key properties of materials is the rate of resistance to impact. This illustrates materials ability to withstand accidental puncturing and can decide the materials ability to success or failure in particular application. This fact is least well defined properties for polymer technology. Although main impact test data in detail is listed in the literature but most of this data is of little value in practice, because impact strength is not among those material properties where the values are universal for every specific application. There is wide range of different variables affecting the material impact strength such as temperature, rate of strain, stress system, anisotropy, the geometry of the component, fabrication condition and environment etc. This fact result from time to time poor correlation between different laboratory data and it can bring up serious problems and confusion in the mind of designer about the use of the material. Just to overcome this problem, very acceptable designs are achieved by using the impact data obtained under practical conditions which is preformed in a environment as close as possible to the service conditions for the material. Data values listed in the literature are used for the initial selection of a material for a specific purpose based on the desired level of toughness. This chosen material should anyway be tested under its final operational conditions in order to improve and guarantee that it is in a satisfactory state to perform its function. And to avoid fracture problems it is essential to minimize the factors which will cause brittleness for sure. These factors include stress concentrations and low temperatures.

R.J. Crowford, 1998, Linacre House. Jordan Hill, Oxford OX2 8DP 225 Wildwood Avenue, Woburn, MA 01801-2041, *Plastic Engineering* – 3rd ed. pp. 147-149

9.1. Factors Affecting Impact Strength

Factors which can effectively affect impact behaviour in material are mostly and mainly fabrication defects. Examples of these defects are internal voids, inclusions and additives such as pigments etc. all of which can cause stress concentrations within materials core. Other factors can be internal welds caused by the fusion of partially cooled melt fronts which usually cause the week areas in the material. As discussed in previous chapters, environment plays a vast roll in affecting materials impact behavior. Polymeric materials become gradually more brittle as they are exposed to sunlight or UV-radiation and weathering for prolonged periods. Some polymers are easily affected by very simple and non toxic fluids e.g. domestic heating oil's act as plasticizers for polyethylene (PE). Even water can have magnificent effect on polymers impact behavior.

Surface finishing of the specimen may also affect impact behavior; in the way that machined surfaces usually have tool marks on them which act as stress concentrations. Some molded surfaces have a characteristic skin layer on the top which can provide some protection against crack initiation. Once the molded surface is scratched, then this protection can no longer exist on the material. According to the experiments and measurements, tamped surfaces for decoration purposes on molded parts can cause a considerable reduction in impact strength in the material.

R.J. Crowford, 1998, Linacre House. Jordan Hill, Oxford OX2 8DP 225 Wildwood Avenue, Woburn, MA 01801-2041, *Plastic Engineering* – 3rd ed. pp. 152-154

10. REINFORCED FABRICS

Before fibers are bonded to the matrix they need to be manufactured with the desired material in the individual method which calls preform. These fiber preform are generally manufactured in sheets, continuous mats or as continuous filaments for spray applications. The main four methods for manufacturing the fiber preform in textile processing techniques are weaving, braiding, knitting and stitching.

There are two main types of fabric forms available in composite industry: the woven fabrics and nonwoven (non-crimp) fabrics. Woven fabrics are mostly used in applications such as containers, barge covers, and water tower blades and in other marine wet lay-up applications. These fabrics are woven into mats in a single layer. Common wave styles are demonstrated in Figure 10.1. The weave pattern will control the amount of fibers in different directions. In unidirectional woven fabrics, the fibers are setup in a way that the fibers positioned in 0˚ are up to 95 % of the total weight of the fabric. The weights of fibers in 0˚ and 90˚ directions are equally distributed through the whole fabric. The fabrics come also in hybrid form in various combinations, such as glass/carbon and aramid/carbon. To protect components from lightning strikes in some applications, conductive wires are woven into the fabric to prevent damage to prevent damage to the material. Figure 10.2 shows the schematic of nonwoven fabric. The fiber directions can be arranged to meet specific mechanical performance requirements of the composite by varying the orientation.

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, *Composites manufacturing : materials, product, and process engineering*, ch.2.4

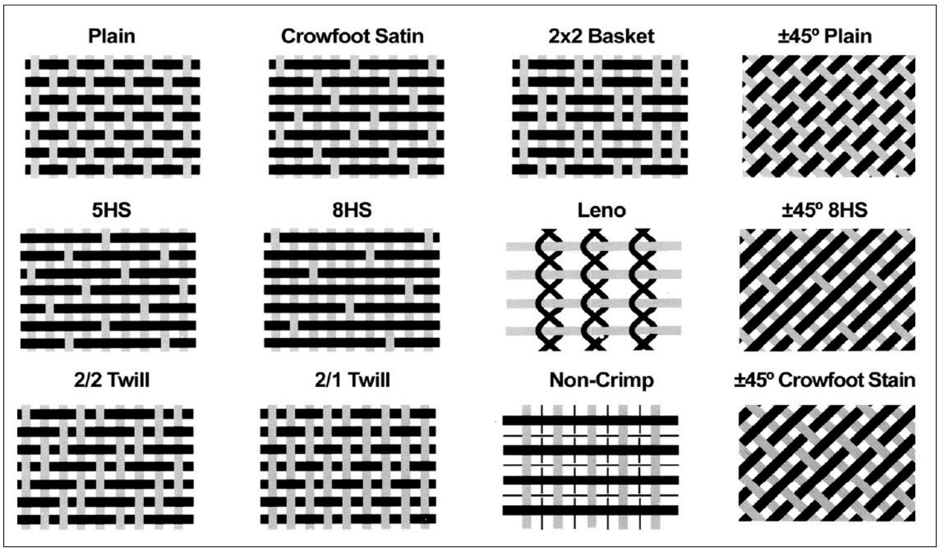

Figure 10.1. Different weave style for composite fabrics.

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, *Composites manufacturing : materials, product, and process engineering*, ch.2.8

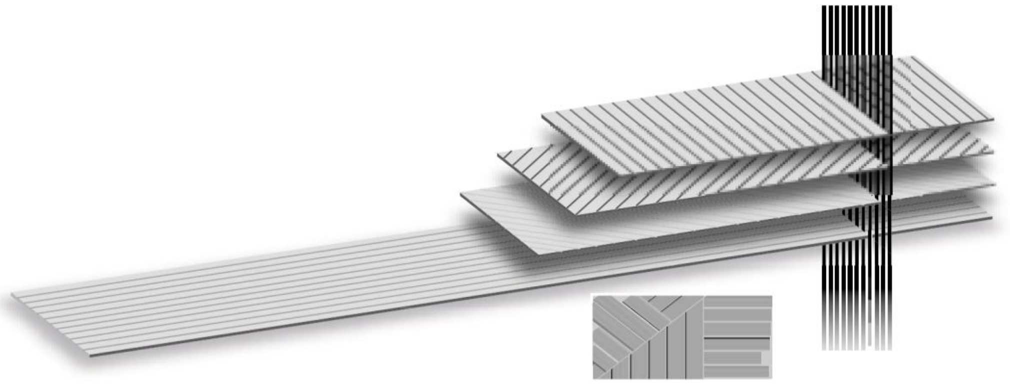

Figure 10.2. Schematic of nonwoven composite fabric.

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 6, Accessed 10.3.2010

http://www.formulaschools.com/curriculum/prepregtechnology.pdf

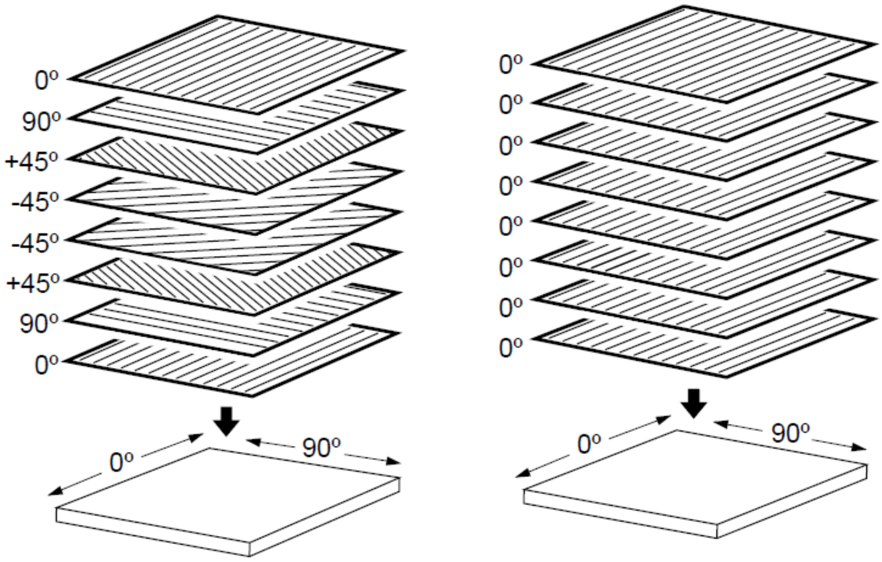

Figure 10.3. Placement of fabric angles in relation to each other. (Multi- and Unidirectional) Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 22, Accessed 10.3.2010

http://www.formulaschools.com/curriculum/prepregtechnology.pdf

11. COMPOSITE MATERIAL MANUFACTURING METHODS

The methods used for manufacturing parts using fiber reinforced material are divided into three main categories. These categories are manual, semi-automatic and automatic methods.

- The *Manual process* contains methods such as hand lay-up, spray-up and autoclave.
- The *Semi-Automatic* process contain cold pressing, hot pressing, resin injection and compression molding of Sheet Molding Composite (SMC)..
- The *Automatic* process includes pultrusion, filament winding, centrifugal casting and injection molding.

11.1. Manual Processing Methods

Manual method of processing is a simple and a basic method producing composites. This method is discussed in this chapter.

11.1.1 Hand Lay-Up

Hand lay-up method is the most widely used processing method in fiber reinforced material industry. The biggest advantage with this method is that it is very simple and very little complicated and special equipment are needed and the molds used in the process can be made out of plaster, wood, metal and/ other materials. In order to start the process, the first step is to cover the mold with a release agent to prevent molding sticking to it. The agent used for this operation is a pure resin called gelcoat. On top of the gelcoat comes a tissue mat to back up the gelcoat and improve the impact strength of the surface and conceals the coarse texture of the reinforcement. After the gelcoat is cured, the main reinforcement is applied on top of it. The resin (unsaturated epoxy or polyester is the most common) is then brushed on together with layers of glass-fiber mat positioned by hand on top of all, as shown in Figure 11.1. The strength of the composite can easily be controlled by adding further layers of mat used for the part.

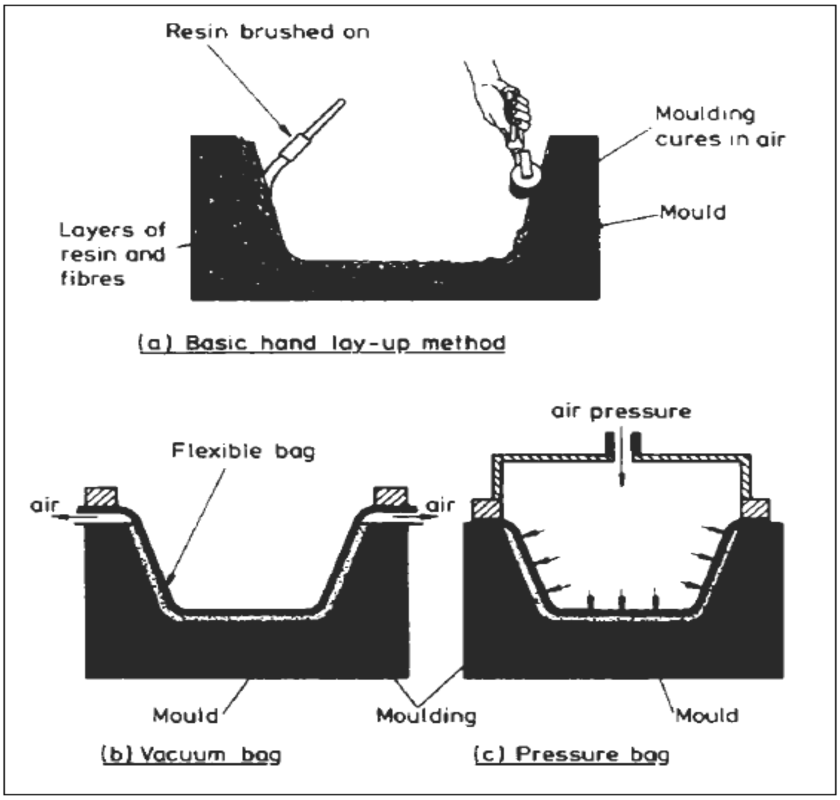

Figure 11.1. Hand Lay-up Method (a. Hand Lay-up, b. Vacuum Bag and c. Pressure Bag)

Different techniques such as *Vacuum Bag Molding* and *Pressure Bag Molding* can be used for this basic process as shown in Figure 10.2. After the mat layers a flexible bag is clamped over the lay-up and a vacuum is applied between the molding and the bag. The pressure bag molding is very much similar to the vacuum bag molding, except the vacuum is applied to the system in the form of air pressure from above.

11.1.2. Spray-Up

The preliminary stage of this method is similar to the previous Hand Lay-Up method but the difference is that instead of using fiber mats, the reinforcements are applied using spray gun. The fiber strands are chopped in a chopper unit and then are sprayed on the mold simultaneously together with the resin as shown in Figure 11.2. The quality of the final material depends on the skills of the spray gun operator, since he controls the overall thickness and the fiber/resin ratio of the composite.

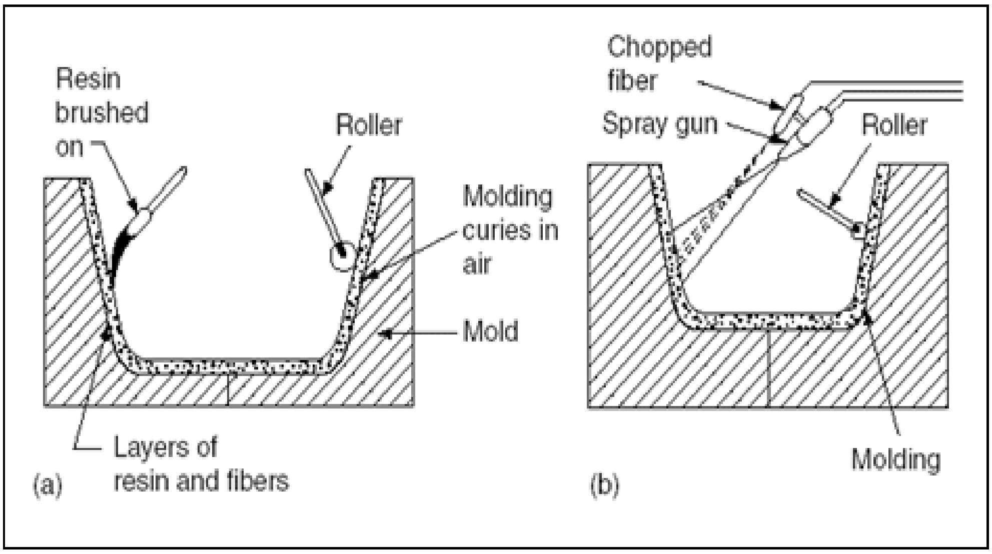

Figure 11.2. Spray-Up Method (b)

11.1.3 Autoclave Molding

In order to produce parts with high precision moldings and high quality, it is necessary to full control over fiber alignment and consolidation of the fibers in the matrix. To achieve this reinforced material, the prepreg (i.e. the fiber mat pre-impregnated with the matrix material) are aligned very carefully and precisely onto an open mold, in Figure 11.3. The arrangement of the fabric layers will determine the anisotropy degree in the molded article. The prepreg stack is then covered with a series of bleeder and breather sheets and finally all layers are covered with a flexible vacuum bag. The air is then extracted from between the flexible bag and the prepreg stack and squeezed tightly on to the mold. The whole assembly is then placed into a very large oven called **Autoclave** for curing.

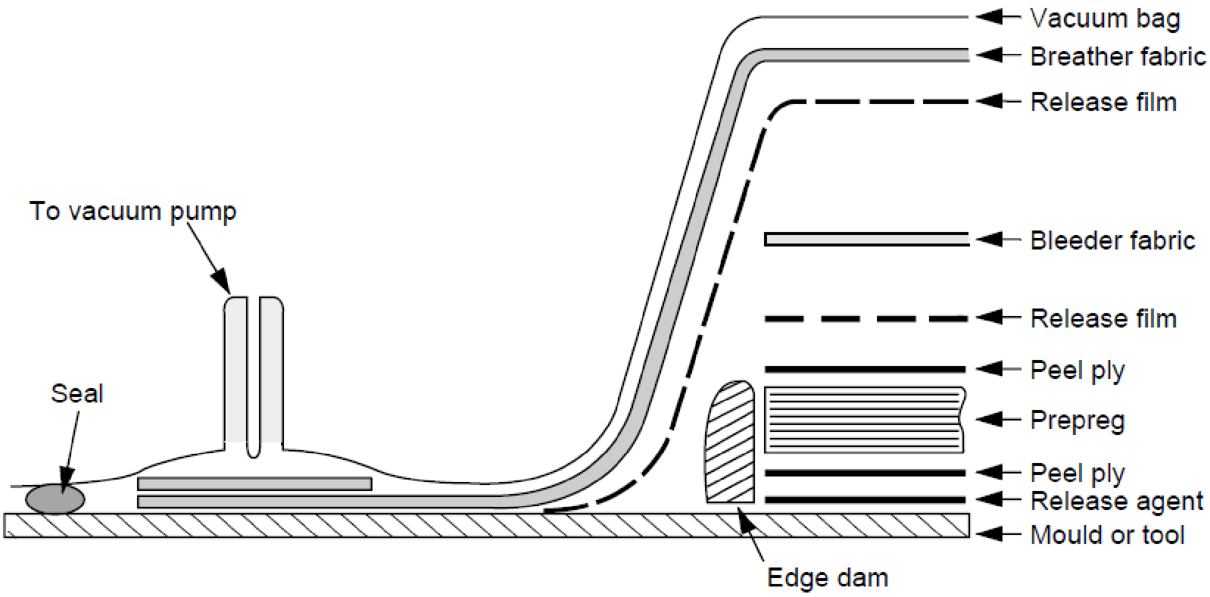

Figure 11.3. Schematic cross section of autoclave molding process.

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 15, Accessed 10.3.2010

http://www.formulaschools.com/curriculum/prepregtechnology.pdf

11.2. Semi-Automatic Processing Methods

Semi-Automatic method is used in industries where partly machines and partly men workforce are participated in the production.

11.2.1 Cold Press Molding

This method employs pressure applied to two halves of a mold in process to disperse resin trough a fabric stack placed in the mold. Release agents and gelcoat are applied on the both male and female side of the mold and the fabric layers are then placed on the female side of the mold. The activated resin is the poured on top of the mat and when the mold is closed the resin will then spread throughout the reinforcement. A typical value of cycle time for this process is usually between 10 – 15 minutes. The process is illustrated in Figure 11.4.

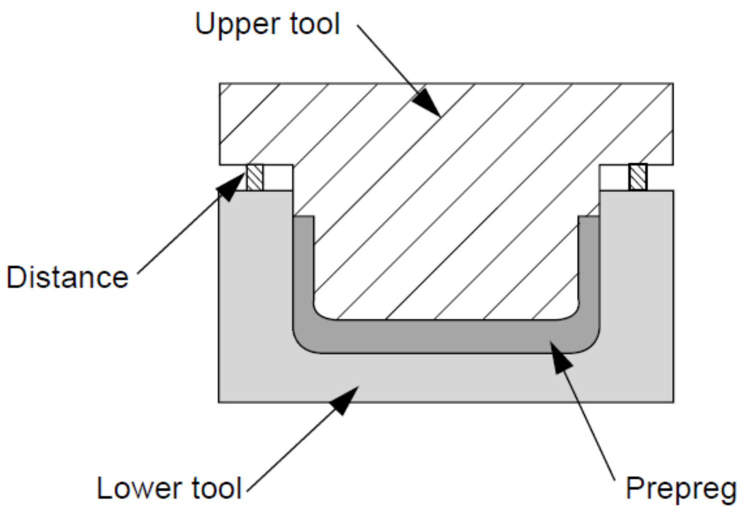

Figure 11.4. Cold Press Mold Process

11.2.2. Hot Press Molding

In this process the curing of the reinforced plastic is accelerated with help of heat (≅180˚C) and pressure (≅15MN/m^2). The common heading of Hot Press Molding contains both Pre-form Molding and Compression Molding.

11.2.3 Compression Molding

Sheet Molding Compounds SMC is completed as a flexible sheet which consists of a mixture of chopped strands mat or chopped fibers (25% by weight) pre-impregnated with resin, fillers and pigments. The whole mixture is placed between the halves of the heated mold. the pressure applied in the mold forces the sheet to take up the contours of the mold. It is not necessary to pour on resin which makes the process more comfortable. The process of SMC manufacturing with compression molding method is shown in Figure 11.5.

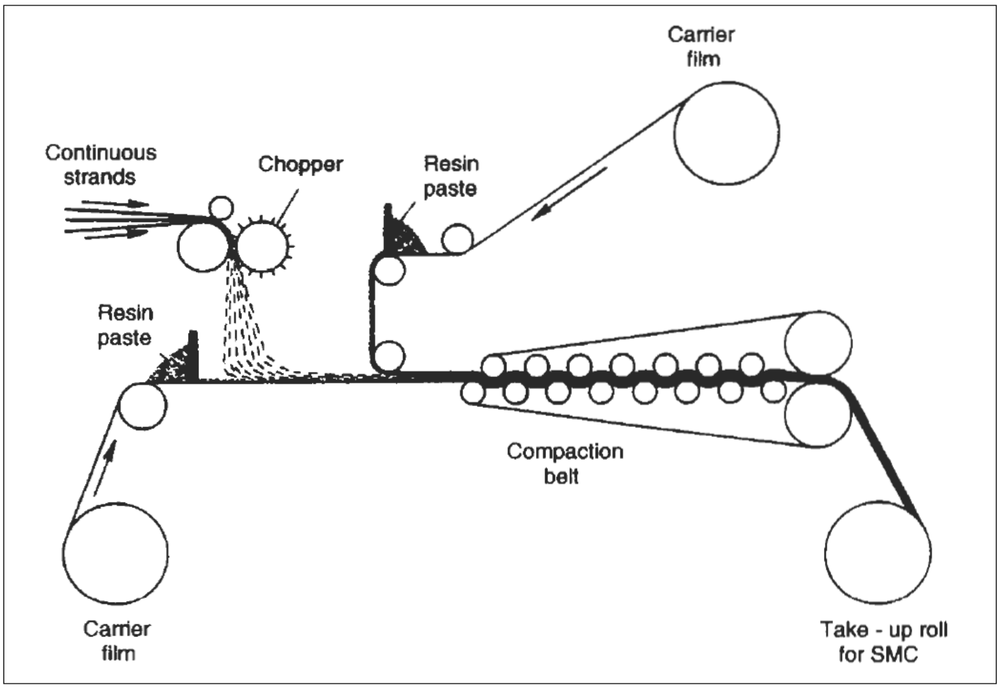

Figure 11.5. Manufacturing of SMC Material with Compression Method

11.3. Automatic Process

Automatic composite manufacturing is the most complex and high-tech method where almost no person is included in the manufacturing process.

11.3.1. Filament Winding

This method includes continuous strands of reinforcements to get maximum benefit from the fiber strength. For this process strands are passed through a resin bath and then wound on to a rotating mandrel. The reinforcement can be laid down in any desired approach by arranging the fibers to traverse the mandrel at a controlled and or programmed mode, as illustrated in Figure 10.7. This system provides very high strength to be achieved and is suitable to parts where reinforcement in the highly stressed hoop direction is important.

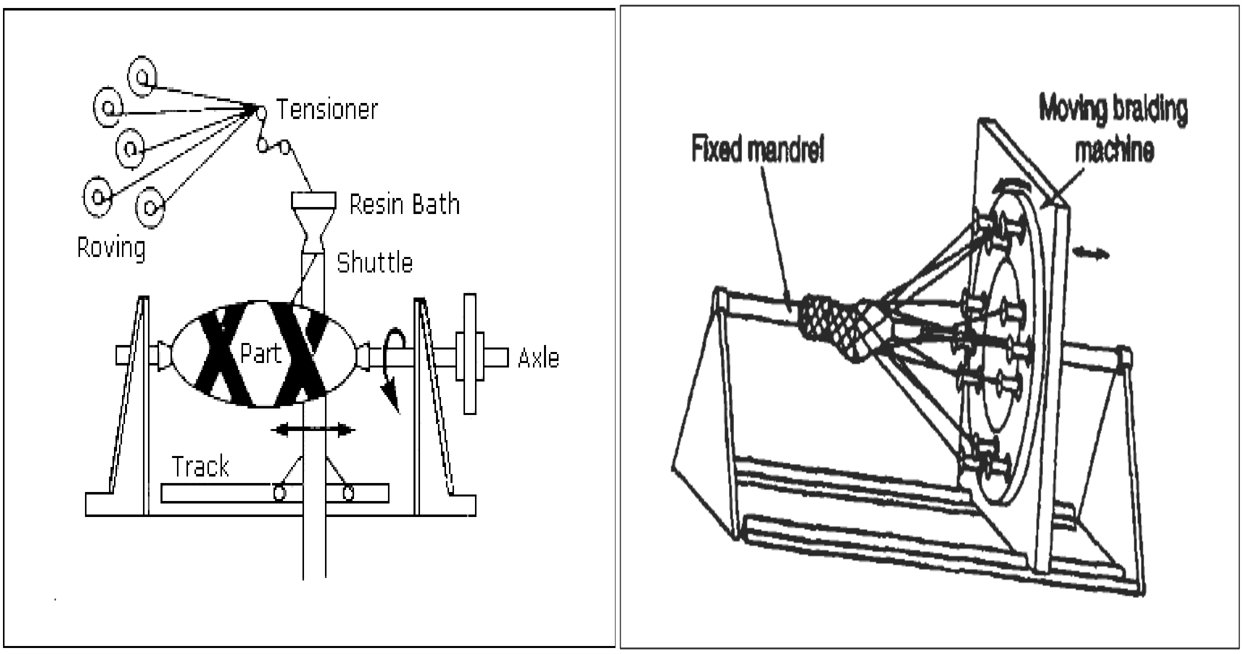

Figure 11.6. Two Types of Filament Winding

http://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_1.html Accessed: 23.11.2009

12. MACHINING AND CUTTING OF COMPOSITES

There are different types of machining operations, such as cutting, drilling, routing, trimming, sanding and milling preformed to achieve various objectives. These operations are the same as for metal machining. Machining of composite parts will create discontinuity in the fibers and will affect the performance of the part and consequently expose the fibers to chemicals and moisture. If the temperature of the machining exceeds the cure temperature of the resin, there will cause disintegration in the fibers and the matrix material. Because of the low thermal conductivity of the composite, there will be heat build-up in the cutting zone. A suitable coolant should be used to dissipate the heat from the tool and workpiece. In drilling metal components, chips absorb 75% of the produced heat while the tool and the workpiece absorb 18% and 7% respectively. In drilling carbon/epoxy composite, the tool absorbs half of the produced heat and the remainder is equally absorbed by the workpiece and the chips. Figure 12.1 demonstrates the occurrence of delamination in carbon/epoxy caused by drilling.

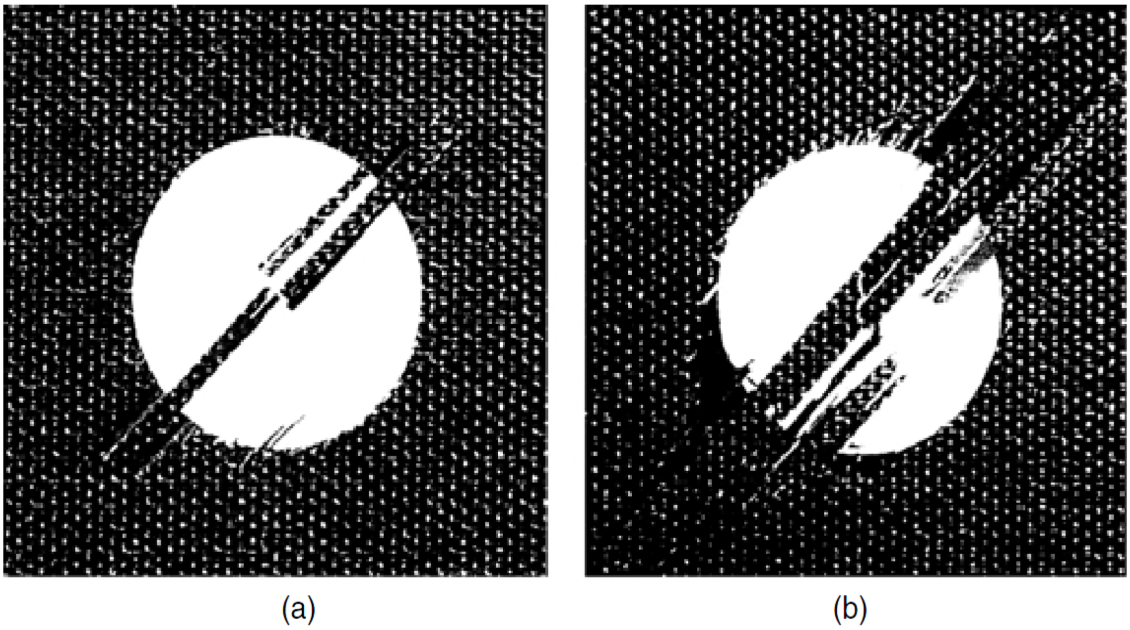

Figure 12.1. Delaminations on carbon/epoxy composite caused by drilling with (a) pointed drill and (b) blunt drill.

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13. RECYCLING OF COMPOSITE MATERIAL

With the increase of composite usage, the concern for recycling of these materials has also increased. Engineers and researchers have developed ways to recycle these materials. The two common methods used for composite recycling are regrinding and pyrolysis.

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13.1. Pyrolysis

In this method the composite material is decomposed at elevated temperature in the absence of oxygen. The polymer will break down in to reusable hydrocarbon fractions as monomers, fuels and chemicals and thus preserves insufficient petroleum recourses. This separates the fibers from matrix and makes it reusable as fillers or reinforcements. A schematic diagram of a pyrolysis process is illustrated in Figure 13.1. Pyrolysis includes a shredder or grinder, reaction chamber, furnace, condenser and storage tank. The polymer matrix separates from the fibers while it's converted into low-molecular- weight hydrocarbons and catalysts as it turns into gas. The collected hydrocarbons are then used as fuels. Through pyrolysis process the composite waste turns into 30% gas and oil, and 70% solid by-product.

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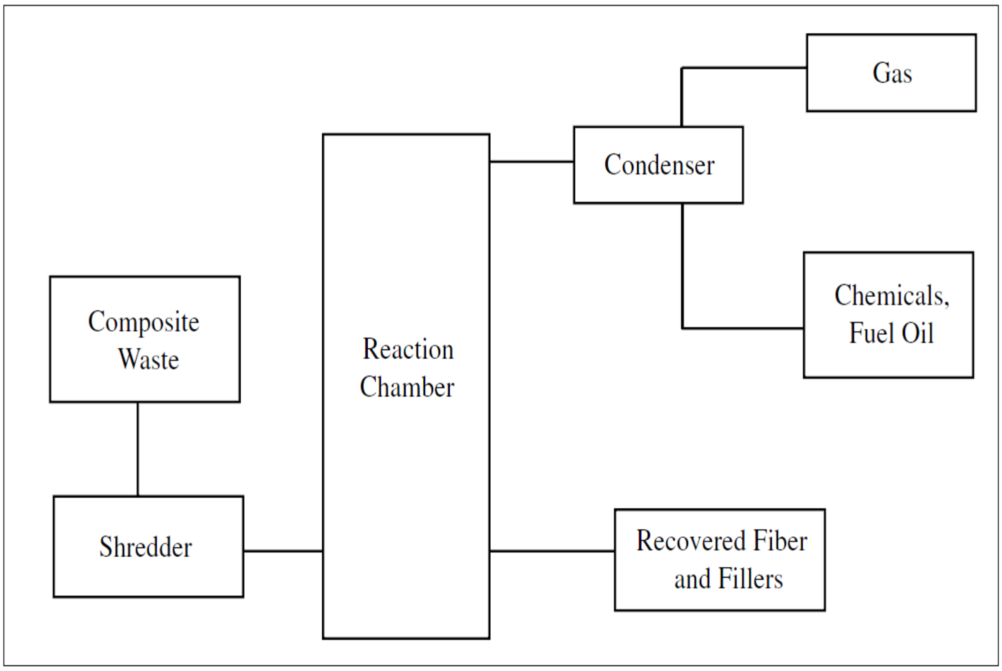

Figure 13.1. Schematic for Pyrolysis Process

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13.2. Regrinding

This method is a secondary recycling process in which the composite waste is ground in to suitable sizes to be reused as fillers. The type of polymers used in the composite decides which application it can be reused in. For a thermoplastic matrix, the resulting materials are used in injection molding and compression molding processes.

Mazumdar, Sanjay K. 2001, CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431, *Composites manufacturing : materials, product, and process engineering*, ch.12.0

14. DESIGN of the Test Specimen

In this chapter, the design and lamination method of the thesis authors own work together with the machining and final lamination of the part are brought up. In addition, the testing method applied on the specimen is analyzed and the result, which explains the purpose of this thesis work in practice, is introduced together with the momentum (14.1), kinetic energy (14.2) and work energy (14.3) formulas whit help of which the final result is determined.

$$p = mv \tag{14.1}$$

$$E_k = \frac{1}{2} m v^2 \tag{14.2}$$

$$\Delta E = W = \int F \, ds \tag{14.3}$$

To achieve this goal, three sandwich structures with the same primary material but different foam thickness are going to be designed and manufactured and then measured to determine and evaluate the impact strength to the core of the construction. Besides, a compression test is going to be performed during the experiment with the help of the tensile testing machine. The values obtained from the test will be tabulated, and the results will be compared with each other.

14.1. The sandwich structure

The test sample is made out of four different components. This composite test specimen is designed in five layers. The first layer is a unidirectional carbon fiber prepreg sheet, which is on the bottom and a layer of paper honeycomb with a depth of 2 cm and 3 mm in cell diameter on the top of the prepreg goes as the second layer. Next, another layer of unidirectional carbon fiber prepreg is placed on top of the honeycomb, parallel to the fiber direction of the previous layer. The forth layer consists of AIREX C52, which is industrial processing foam. It has a unique functional surface made of thermoplastic bonded polyester fibers that minimize resin consumption, while its perforation ensures a good linkage to the lamination. Here, AIREX C52 with a thickness of 2 cm is the last component completing the sandwich structure and it is the part that works as impact absorber. In the end, a layer of biaxial carbon fiber sheet is laminated over this sandwich composition with epoxy resin, to close the sandwich part into one single composite structure. Figure 14.1 is the actual formation of the sandwich structure with dimensions of 20 mm honeycomb and 15 mm foam.

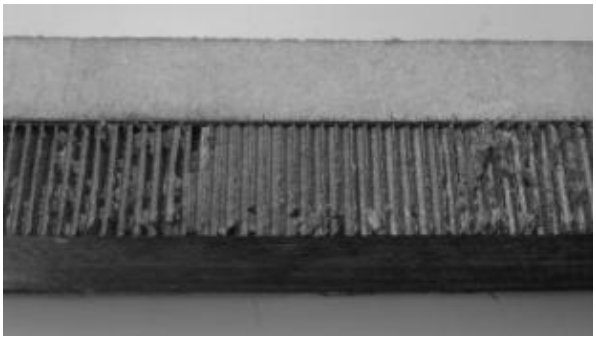

Figure 14.1. The layer formation in the sandwich structure.
Authors own work

14.2. Sandwich Structure Lamination

The process for laminating the early shape for the sandwich structure in order to make the prepreg keeping the structure together is performed in two stages. The assembly and fixture of the material in one part is achieved by using partly vacuum bag lamination method and partly autoclave method. The sandwich structure is packed and sealed in a vacuum bag and the whole system is then placed in an oven at 180 ^{o}C over 6 hours under a pressure of 0.2 bar for the prepreg to activate. Figure 14.2 is the standard diagram for laminating prepreg material. The composite structure for this research was laminated according to the graph in Figure 14.3 due to the poor and old quality of the prepreg material used in the manufacturing of the product. After the process, the part is ready for the next step that is processing the part to the planed measurements for desired result.

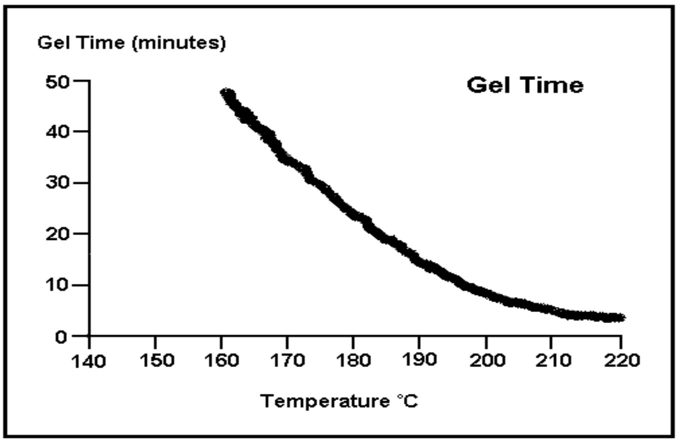

Figure 14.2. Gel time versus the oven temperature according to Hexcel product information sheet.

Hexcel Composites, Duxford, 1997, Publication No. FGU 01, PREPREG TECHNOLOGY, pp. 16, Accessed 10.3.2010

http://www.formulaschools.com/curriculum/prepregtechnology.pdf

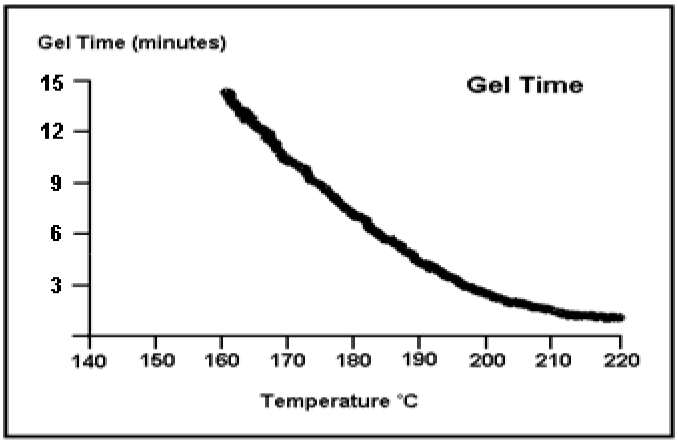

Figure 14.3. Graph used for laminating the piece for this thesis.

Authors own work

14.3. Modifying the Test Piece

To get the right thickness on the impact absorber material, for testing the minimum size to obtain the best result, the part modified by milling process which makes the thickness of the foam material into four different sizes. The target sizes for these tests are 20 mm, 15 mm, 10 mm and 5 mm.

14.4. The Complete Lamination of the Part

The method used for final lamination of the sandwich structure is vacuum bag lamination. For this method the sandwich structure is once again sealed with a vacuum bag together with the biaxial carbon fiber sheet on top of it. Two omega profiles are placed on top of the carbon fiber sheet in the way that one creates underpressure (0.2 bar) and the other one transfers the epoxy resin throughout the carbon fiber surface. Omega profile is a longitudinally cut hose which looking at it from the either sides it looks like the Greek letter omega (Ώ). Omega profile is made of silicone so it will not get glued to the resin. Figure 14.4 illustrates the lamination in real time. The maximum distance between the omega profiles is 30 cm in order to make the resin transfer in the correct and easy way. The resin can be transferred maximum 30 cm with the applied underpressure. The epoxy resin used for this lamination is of type Ampreg 21, including the standard hardener. The resin to hardener ration is 3:1 and according to the manufacturer table, the gel time is 58 minutes under constant pressure.

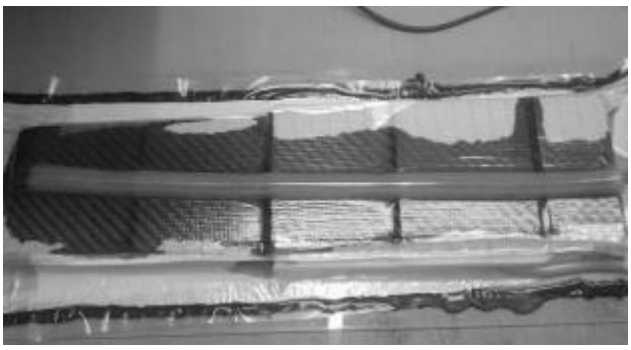

Figure 14.4. Picture of test specimen in lamination process.

Authors own work

14.5. The Impact/Compression Test

The main goal of this test is to measure the energy absorption by the foam in the sandwich material, the purpose of which is to protect the core of the structure and calculate the minimum energy required before the core of the structure (the honeycomb) is damaged. This test measures the weight and the speed of any object colliding with the surface of the material before it penetrates the entire structure with the specified properties.

In order to proceed with the test and to obtain an accurate result for maximum energy for penetrating the foam and in the worst case the whole material, the test was done on a testometric machine. Each test specimen was compressed and penetrated with two different ball bearing sizes (13.5 mm and 21 mm in diameter) using the testometric machine shown in Figure 14.5 and Figure 14.6. The aim of using these two ball bearings with different sizes for compressing the test pieces is to obtain initial data and information from the characteristic of the sandwich structure, and to be able to compare different forces and energies of the object colliding with the surface of the structure. All in all, eight penetration tests were performed on the specimen. All the data was documented and illustrated as diagrams to enable clearer understanding and easier comparison between the thicknesses of the material and the mass of the object penetrating the surface.

Figure 14.5. The method of compression with testometric machine

Authors own work

Figure 14.6. The close-up of the compression process

Authors own work

The testometric machine is mainly used for laboratory tests in form of tensile testing or compression testing. The specimen is placed in the machine between the grips and an extensometer can automatically record the change in gauge length during the test. The dimensions of this machine are 2 m in length, 0.5 m in width and 0.5 m in thickness. The maximum force this machine can apply both in tension or compression is 5 kN. For this research the machine is performing a compression test by using a handmade adapter device to keep the ball bearing into its place.

15. RESULT

The result of all the tests is illustrated in this chapter. Every diagram is presented with detailed explanation and interpretation. These results are specified only for the two mentioned ball bearings with their fixed dimensions. Later in this chapter, a formula is presented with which the weight and speed of the object can be calculated and determined to optimize the thickness of the impact absorber layer (the foam) in the structure for different environment and application.

15.1. Force Distribution Results

In order to determine the force distribution throughout the structure while penetrating the whole material with the ball bearings which are selected only for this research, Figure 14.1 illustrates the force diagram for all layers in the material using a ball bearing with a dimension of 13.5 mm in diameter to compress it. The diagrams explains the force the ball bearing applies on every layer of the structure before it penetrates the whole material starting from the test piece 30 mm structure with a 5 mm thick foam, 35 mm structure with a 10 mm thick foam, 40 mm structure with a 15 mm thick foam, 45 mm structure with a 20 mm thick foam. Figure 14.2 illustrates the same results as for Figure 15.1, except for the ball bearing with 21 mm in diameter.

All the extreme values from these graphs are tabulated in Table 15.1 and Table15.2 and they are placed together with the schematic drawing, Figure 15.3, of the structure to illustrate the force distribution trough each and every layer.

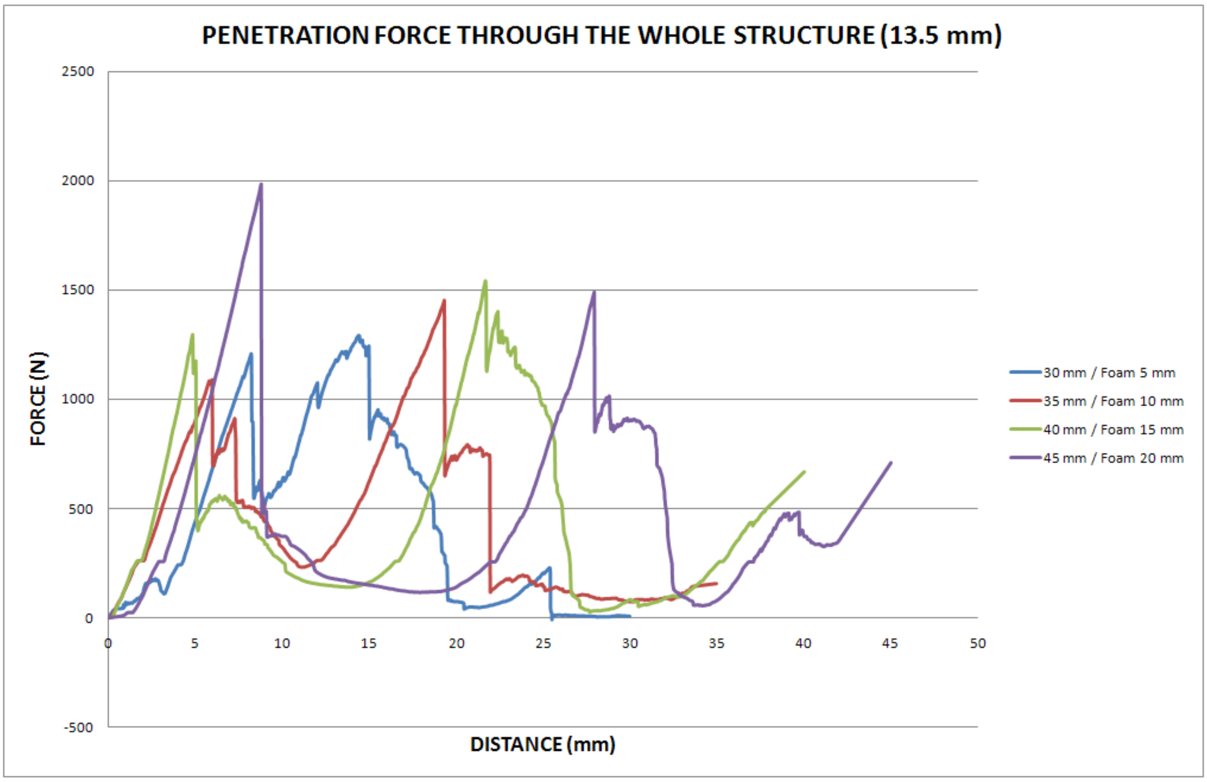

Figure 15.1. Penetration Force through the whole structure, ball bearing with diameter 13.5 mm.

Table 15.1. The extreme values from Figure 15.1.

13.5 Ball bearing			
Foam	**Distance**	**Force (N)**	**Explanation:**
5 mm	8 mm	1175.8	Penetrating carbonfiber lamination and foam
	14 mm	1293.4	In contact with honeycomb
	25 mm	207.3	Penetrating the honeycomb
10 mm	6 mm	1090.1	Penetrating carbonfiber lamination
	7 mm	913.2	Penetrating foam
	19 mm	1182.5	In contact with Prepreg
	21 mm	752	Penerating prepreg and in contact with honeycomb
15 mm	5 mm	1293.6	Penetrating carbonfiber lamination
	7 mm	550.3	In contact with foam
	22 mm	1512.4	Penetrating foam and in contact with prepreg
	23 mm	1310.6	Penerating prepreg and in contact with honeycomb
20 mm	9 mm	1983.2	Penetrating carbonfiber lamination and foam
	28 mm	1488.5	Penetrating foam and in contact with prepreg
	29 mm	1006.6	Penetrating prepreg
	40 mm	443.4	Penetrating the honeycomb

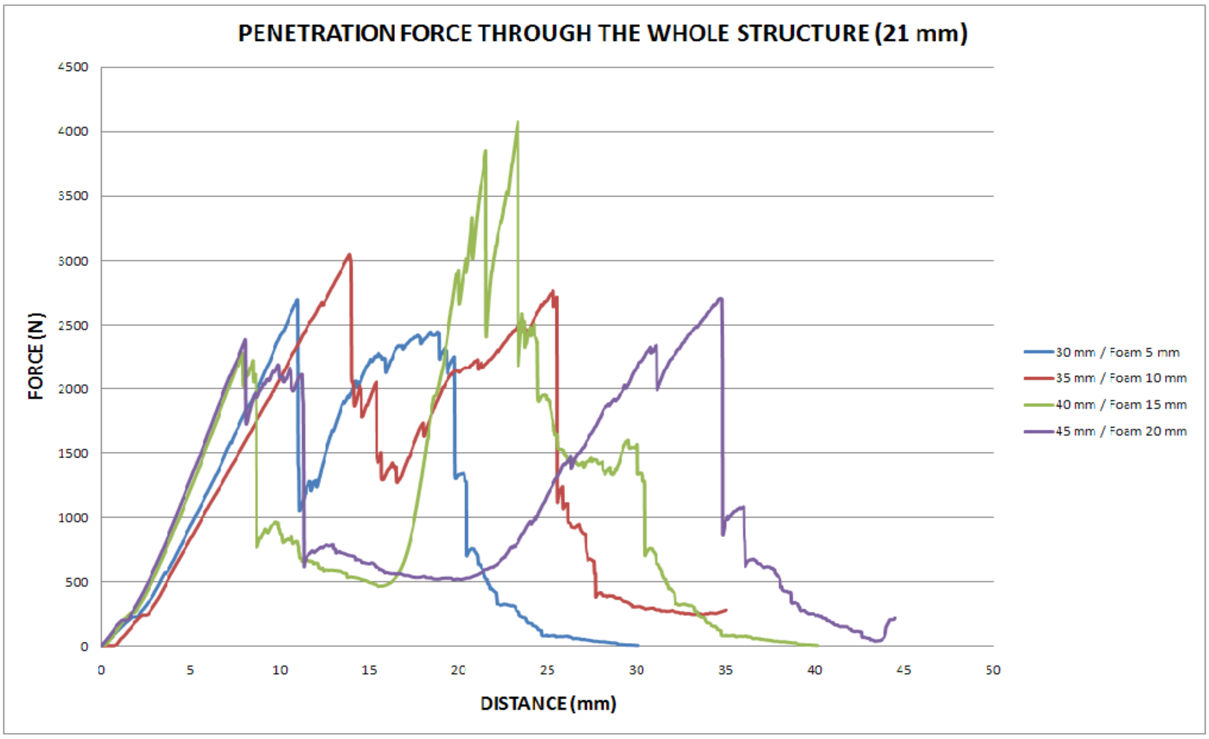

Figure 15.2. Penetration Force through the whole structure, ball bearing with diameter 21 mm.

Table 15.2. The extreme values from Figure 15.2.

21 mm Ball bearing			
Foam	**Distance**	**Force (N)**	**Explanation:**
5 mm	11 mm	2699.9	Penetrating carbonfiber lamination and foam
	18 mm	2426.5	In contact with honeycomb
	21 mm	78.74	Penetrating the honeycomb
10 mm	14 mm	3049.2	Penetrating carbonfiber lamination and foam
	14 mm	2126.5	Penetrating foam
	16 mm	1397.3	In contact with Prepreg
	25 mm	2762.1	Penerating prepreg and in contact with honeycomb
15 mm	6 mm	2392.8	Penetrating carbonfiber lamination
	16 mm	550.3	In contact with foam
	24 mm	4116.9	Penetrating foam and in contact with prepreg
	30 mm	1592.4	Penerating prepreg and in contact with honeycomb
20 mm	7 mm	2753.5	Penetrating carbonfiber lamination and foam
	20 mm	626.7	Penetrating foam and in contact with prepreg
	32 mm	1979	Penetrating prepreg
	36 mm	1153.6	Penetrating the honeycomb

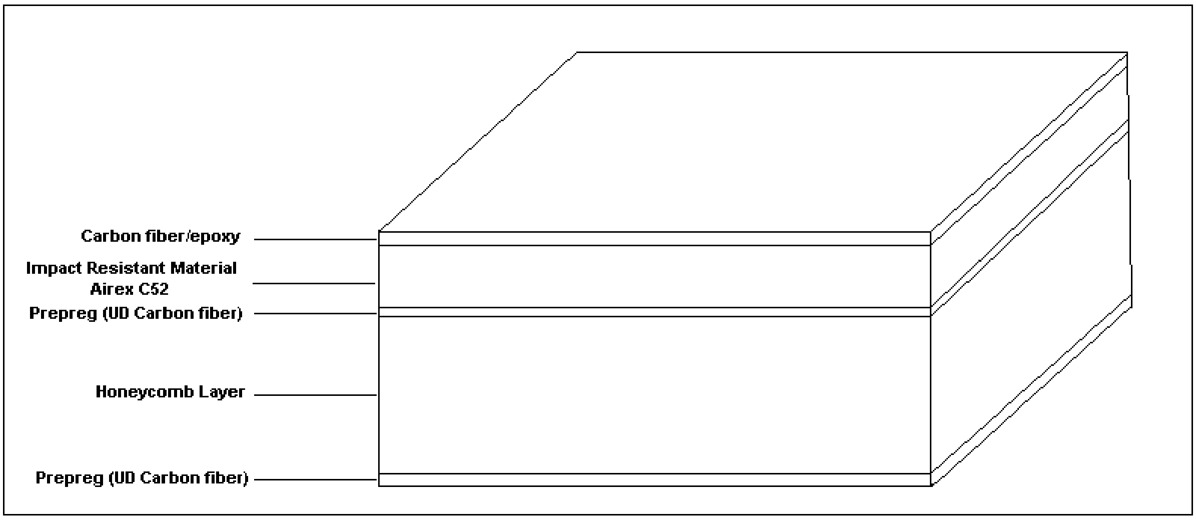

Figure 15.3. Schematic figure of the sandwich structure.

15.2. Energy Distribution Results

The energy distribution is calculated for the ball bearing to penetrate the whole material. The following diagrams showing how much energy was absorbed by the foam before the honeycomb were damaged. Figure 15.4 and Figure 15.5 illustrating the energy required penetrating trough the whole material for both ball bearing sizes (13.5 mm and 21 mm). Figure 15.6 and Figure 15.7 demonstrates the energy absorption by the AIREX C52 foam in composite material for the same ball bearings. The diagrams contain the maximum energy value for every layer. Tables 15.3, Table 15.4, Table 15.5 and Table 15.6 show the maximum energies for every experiment.

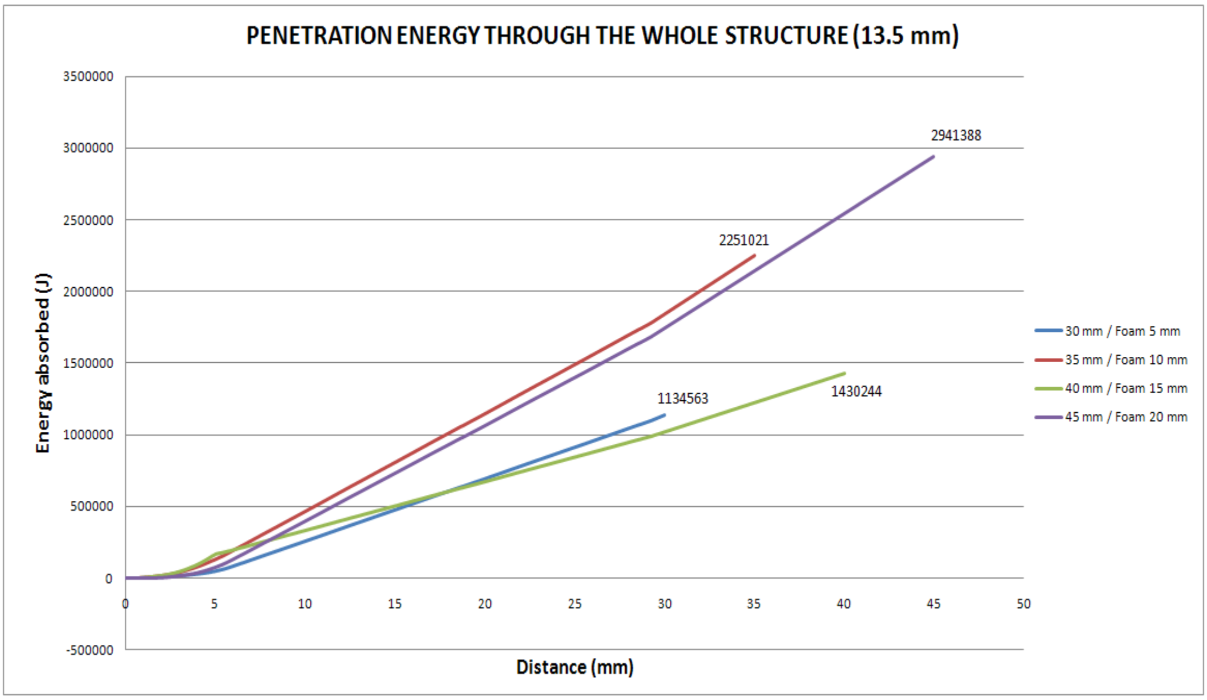

Figure 15.4. Penetration energy through the whole structure, ball bearing with diameter 13.5 mm.

Table 15.3. Maximum energy values for Figure 15.4.

Maximum Energy Values for 13.5 mm	
Distance (mm)	Energy Absorbtion (J)
30	1134563
35	2251021
40	1430244
45	2941388

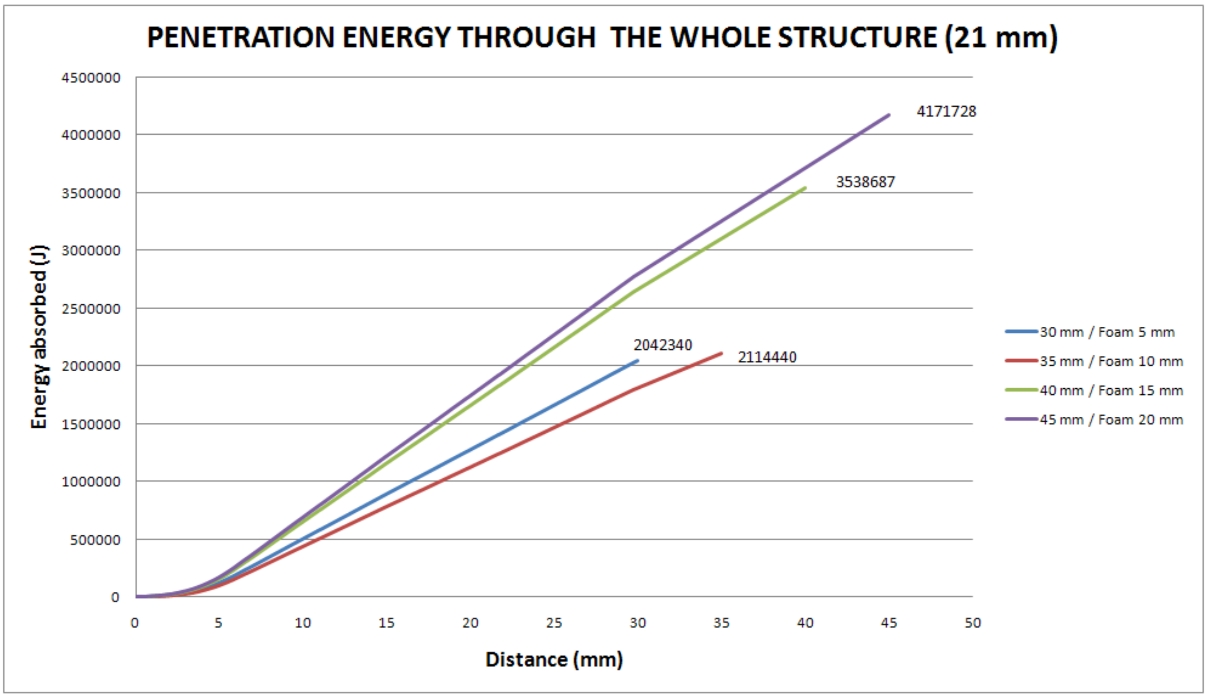

Figure 15.5. Penetration energy through the whole structure, ball bearing with diameter 21 mm.

Table 15.4. Maximum energy values for Figure 15.5.

Maximum Energy Values for 21 mm	
Distance (mm)	Energy Absorbtion (J)
30	2042340
35	2114440
40	3538687
45	4171728

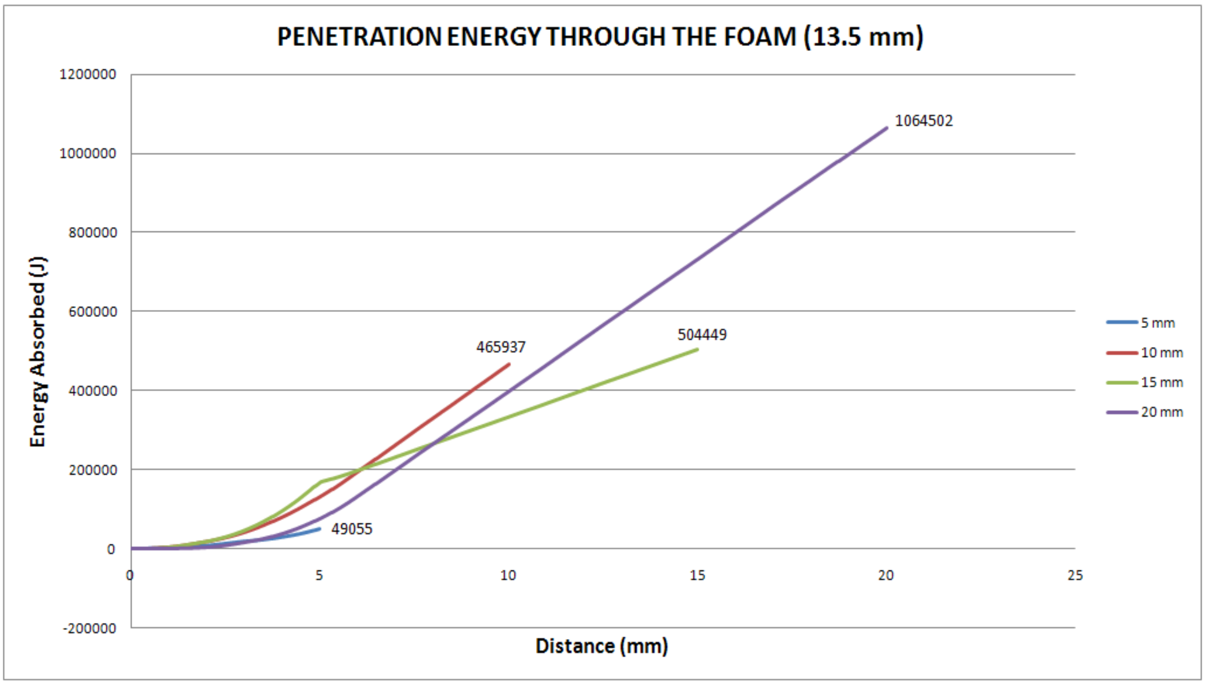

Figure 15.6. Penetration energy through the foam, ball bearing with diameter 13.5 mm.

Table 15.5. Maximum energy values for Figure 15.6.

Maximum Energy Values for 13.5 mm	
Distance (mm)	Energy Absorbtion (J)
5	49055
10	465937
15	504449
20	1064502

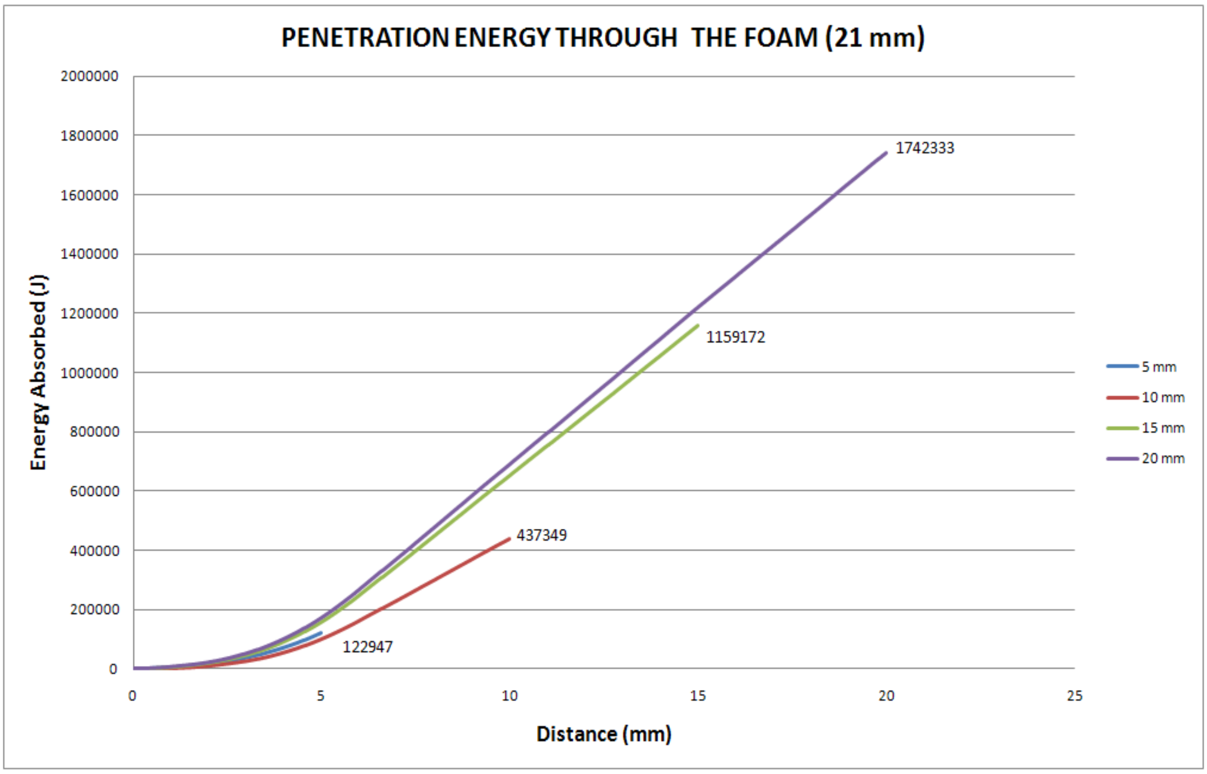

Figure 15.7. Penetration energy through the foam, ball bearing with diameter 21 mm.

Table 15.6. Maximum energy values for Figure 15.7.

Maximum Energy Values for 21 mm	
Distance (mm)	Energy Absorbtion (J)
5	122947
10	437349
15	1159172
20	1742333

15.3. Result Anomalies

This research was influenced by a few facts that could have changed the result of the data. A fact that affected the properties of the material in the test is that the carbon fiber sheet contained dust from the place it was stored. Contaminations did not allow the infusion to be performed in the best way possible. The dust in the fibers increased the friction in epoxy flow and caused the specimen to partly remain unlaminated. This fact caused the part to be laminated twice. As consequence some values in the result could have been affected and the raw data given by the calculations and graph might be deceptive.

15.4. Material Energy Formula

Upon performance of the tests, the formulas for calculating the impact energy absorption for AIREX C52 in the sandwich structure was obtained. This formula enables calculation of impact materials energy absorption along with the parameters for the impacting object, such as speed, mass and are. These formulas are the results of combining momentum formula (15.1), kinetic energy formula (15.2) and work-energy formula (15.3):

$$p = mv \quad , \quad m_1 v_1 = m_2 v_2 \tag{15.1}$$

$$E_k = \frac{1}{2} m v^2 \tag{15.2}$$

$$\Delta E = W = \int F \, ds \tag{15.3}$$

Using these three formulas and combining them in the correct way and taking the energy difference in consideration, will give the compressive modulus value for the impact resistant foam in the material. This value is the compressive strength for the material given in N/mm^2 and demonstrates the toughness of the material in compression.

16. CONCLUSION

The goal of this work was to determine what is the minimum impact energy required to penetrate the impact resistance material. This concept is essential in design and construction of the material for different environment. This research demonstrated the materials impact strength against objects colliding with surface of the structure, and proved that the formulas given in previous chapter can be used to calculate and accurately design the thickness of the impact resistance material due to mass and speed of objects. By finding the kinetic energy for an object before and after collision with the construction and using equation (16.1) and (16.3) the final compressive strength can be determined. In the formula E_0 is kinetic energy of the object and E_1 is kinetic energy of the shelter after being hit. In the end using equation (16.4) and finding K value and determine the compressive strength, it makes the comparison between documented compressive strength and the calculated in the design possible.

$$E_k = \frac{1}{2}mv^2 \tag{16.1}$$

$$v_1 = \frac{m_0}{m_0+m_1} * v_0 \tag{16.2}$$

$$\Delta E = E_0 - E_1 \tag{16.3}$$

$$\Delta E = W = \int F\, ds = \frac{1}{2}Kx^2 \tag{16.4}$$

Finally, the conclusion is that using the formulas determining the values based on which optimization and adjustment of impact resistance foam is possible.

In order to achieve these results, the impact resistance foam was analysed after a compression test. The specimens were penetrated to get the forces over distance and using that data to calculate the energy for every individual test.

In order to make this outcome and result clearer, an example below is given and calculated.

Ex.

A box made of the composite material in this thesis with a mass of 100 kg is thrown out of an airplane with a speed of 20 m/s. To calculate if the impact resistant foam with a thickness of 1 cm will tolerate the impact with a rock with the mass of 5 kg on the ground, the formulas (16.1 – 16.4) are used.

m_{box} = 100 kg v_{box} = 20 m/s x = 1 cm = 0.01 m

m_{rock} = 5 kg v_{rock} = ?

1) The kinetic energy for the box towards the ground is calculated with formula (16.1):

$$E_k = \frac{1}{2}mv^2 \rightarrow \quad E_k = \frac{1}{2}100kg * (20\frac{m}{s})^2 = 20000 \text{ J}$$

2) The velocity for both box and rock is calculated after collision with formula (16.2):

$$v_{rock+box} = \frac{m_{box}}{m_{box}+m_{rock}} * v_{box} = \frac{100\ kg}{105\ kg} * 20\frac{m}{s} = 19.05\frac{m}{s}$$

3) The kinetic energy difference is calculated for both the box and, box and rock together with formula (14.3):

$$\Delta E = E_{box} - E_{box+rock} = 20000\ J - \frac{1}{2} * 105\ kg * (19.05\frac{m}{s})^2 = 947.62\ J$$

4) Next, the value for K (the compressive strength) is determined by using formula (16.4):

The energy difference is set to be equal to the work done by the system.

$$\Delta E = W = \int F\ ds = \frac{1}{2}Kx^2 = 947.62\ J$$

→ if $x = 0.01\ m$ then → $K = \frac{947.62\ J}{(0.01\ m)^2} * 2 = 18952400\ Pa$ = 18.9 MPa

Will this impact resistant foam stand the pressure?

Answer: comparing the answer to the standard registered value for AIREX C52, the maximum compressive strength for it is 25 MPa and the answer obtained from the calculation was 18.9 MPa.

Conclusion: 18.9 MPa is 76 % of standard compressive strength for AIREX C52, is much lower value then what the material can actually absorb, which means that this box will survive the impact.

17. DISCUSSION

The field of composite technology is a very vast. This research was a very small scope concentrated on strength of materials. Results obtained from the tests were quite reliable compared to the standard values documented for all the layers in the structure.

This research was influenced by a few facts that could have changed the result of the data. The prepreg material was not of brand new quality, and it had been stored for over three years therefore the first stage lamination time had to exceed the standard time. Another fact which could affect the properties of the material in the test is that the carbon fiber sheet contained dust from the place it was stored. Contaminations did not allow the infusion to be performed in the best way possible. The dust in the fibers increased the friction in epoxy flow and caused the specimen to partly remain unlaminated. This fact caused the part to be laminated twice.

In the end of the experiment, to prove that the values are valid and the result obtained does comparable with practice, a control test is meant to be done. In this research due to lack of material and time to produce more test specimen, this phase of the test remained undone. All the values, results and conclusions are from the first test specimen.

The comparison of the simulated test on the material is limited to laboratory equipment with which only a theoretical strength of the designed structure is measure. To Test and determine the capabilities of the structure in real life has to be tested in situation of heavy storms or environmental disasters, to actually see the accurate result of the composite structure.

17.1. Cost of the Material

In order to use the structure for mass production, the cost of the final product is very important. The cost of every plays in the structure plays a very critical role in the final product which in this care is carbon fiber. This composite structure can also be manufactured using other materials than carbon fiber such as aramid or glass fiber, but in either case the final result will vary dramatically. According to Kevra Oy companies pricelist, the price for carbon fiber is 28 €/m^2, aramid mat is 23 €/m^2 and Glass fiber is 1.5 €/m^2. The price and the application the the structure will be used in will decide the material choice.

18. SUGGESTION FOR FURTHER WORK

In case of further research on this topic, wider material selection with better quality is recommended. To obtain a good material quality, all lamination sequences needs to be performed in the standard way. No contamination or bubbles should be mixed with the epoxy for the material to be fully laminated. This will cause the matrix to transfer all the pressure equally to fibers and provide a strong reinforced result.

The limitation of material choice limits the research with only using carbon fiber in the structure. Considering the price and mechanical properties of carbon and aramid, using a different material for this research can give different results than only using carbon fiber.

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