Designing in Carbon Fibre Composites

Master of Science Thesis in the Master Degree Programme Product Development

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Katarina Uusitalo

Abstract

The need for lighter vehicles is becoming more and more important for the heavy-duty industry. This can be achieved by using composite materials. One of the most promising materials is carbon fibre reinforced plastics, a composite material with carbon fibres bonded together by a polymer. Carbon fibre reinforced plastics are in many ways different from conventional materials, such as steel that is commonly used in the structural parts today. This project has investigated issues with using carbon fibre reinforced plastics, with a focus on fatigue and how to design in composite materials. In the early phases of the project, a literature review was done, where delamination, galvanic corrosion, fatigue and joining were seen as the most critical problems. This was followed by further investigation of fatigue.

Fatigue is weakening of the material due to cyclic loading and is difficult to predict and to validate because of the inhomogeneous structure of composite materials, and because failure often is sudden and without prior notice. If fatigue is critical is very much dependent on the type of loading and the design of the structure. It is therefore important to have fatigue in mind when designing in composite materials, to minimise its impact and the risk it occur. Many factors affect the material behaviour and that have to be considered when designing in composite materials, such as the material properties and the material design, e.g. the lay-up of the fibres, the manufacturing process, and the design of the structure. The behaviour can also be affected by environmental conditions and the type of load applied to the composite. Due to all those parameters and the complexity of composites it is difficult to give clear directions of how to design in composite materials. There are however general guidelines that have to be followed for most composites, for example the fibre orientation is strongly affecting the strength of the composite. The result of this thesis is guidelines for designing in composite materials, the guidelines states important parameters to have in mind when designing.

Definitions

CFRP – carbon fibre reinforced plastics, composite materials consisting of carbon fibres and a polymer matrix

FRC – fibre reinforced composites

FRP – fibre reinforced plastics

PMC – polymer matrix composites

Quasi-isotropic – the material have an equal number of layers in the 0°, 90°, ±45° directions, so that the material behaviour is the same in those four directions. The composite should also be symmetric and balanced around the midplane.

Unidirectional composite – a composite with all fibres rotated in the same direction

Isotropic – same behaviour in all directions of the material

Anisotropic – different behaviour in the different directions

Interlaminar – in ply interfaces

Intralaminar – in individual plies

Off-axis tensile loading – loading in all directions other than parallel or perpendicular to the fibre direction (Case & Reifsnider, 2003).

Ply – layer with fibres in the composite

[0/90]- the orientation of the fibres, in this case is the fibres oriented in the 0° and 90°-directions, each layer is separated by / so here only two layers is used. If $[0/90]_2$ it means that this is repeated twice, e.g. [0/90/0/90] and if $[0/90]_s$ the lay-up is symmetric: [0/90/90/0].

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1 Introduction

The purpose of the introduction is to give the background, identify the problem and state the aim and purpose of this project. Project limitations, other research and the disposition of the thesis can also be read in this chapter.

1.1 Background

More and more requirements are affecting the heavy-duty vehicles. EU has set the aim to decrease the emissions with 20 per cent compared to today to 2020 (Scania AB, 2011). One way to do this is by reducing the weight of the vehicle. The payloads of the trucks can be increased and the fuel consumption and the associated CO_2 emissions could be reduced by using lightweight materials. Reduced fuel consumption is an important factor for mass production vehicles (Mangino, et al., 2007), and it is estimated that 75 per cent of the fuel consumption is directly related to the weight of the vehicle. The weight of mass transit transportation vehicles and trucks could be reduced with 40 to 60 per cent using composite materials instead of metal. Mass transit vehicles with lower weight have become of interest to the customers. In New Jersey in United States transit authorities have requested buses with a weight of 2.2 tonnes less than the current models and in comparison, a conventional metal frame buss weighs between 12 and 15 tonnes when fully loaded (Vaidya, 2011). One of the most promising composite materials is carbon fibre reinforced plastics, CFRP, a composite material with carbon fibres bond together by a polymer. This type of material is not used for structural parts within heavy-duty vehicles today, but is used within the aerospace industry. The specific modulus and strength of polymer matrix composites are superior to many other materials, which are the main reasons for polymer matrix composites being used extensively in aerospace and transportation (Ning, et al., 2007). Carbon fibre composites are becoming more and more important and the market is expected to grow (Sullivan, 2006); Mangino, Carruthers and Pitarresi (2007) believe that the material have a large future in the automotive sector. Carbon fibre composites are already used in vehicles, mainly in high performance cars where they often are the primary structural material (Mangino, et al., 2007). To meet the environmental obligations from the automotive industry it is expected that the implementation of lightweight materials and design must be included (Mangino, et al., 2007). To develop structures of lightweight material is therefore important for companies within the heavy-duty vehicle industry, in order to keep their position on the market.

1.2 Purpose

The purpose of this project is to gather more knowledge about carbon fibre reinforced plastics, CFRP, and issues that may occur when changing from steel to CFRP in the rear of the bus chassis. The purpose of this project is to ease the future work with a possible change of material, as the usage of CFRP is a very new area within the heavy-duty vehicle industry. It is necessary to gather more knowledge about the usage and manufacturing of CFRP in order to go further, as the material in many ways is different compared to steel. There is also a need for design guidelines and how to design in composite materials.

1.3 Aim

The aim of the project is to identify and evaluate material technical problems that can occur when using carbon fibre composites in the structural parts of a bus chassis, and to formulate design guidelines in order to handle those issues when designing in composite materials. The problems were described according to the manufacturing, processing and the usage of composites in heavy-duty vehicles. One of the identified issues was selected to further investigate. How the four most critical issues affect the designing and dimension process of composite parts were evaluated.

Two research questions were formulated to describe the objective of the project:

> *Which issues, related to material properties, production, processing and usage, may occur when implementing carbon fibre reinforced plastics, CFRP, in the rear of a bus?*

> *What design guidelines can be formulated in order to handle those identified issues in the product development process?*

1.4 Limitations

It is not possible to cover all different composite materials within this project. The project is limited to focus upon CFRP, more specific carbon fibre reinforced with thermosetting resins, and especially epoxy. Carbon fibre reinforced epoxy is one of the most promising options thanks to its excellent mechanical properties and low weight in relation to strength, and would be a good choice for structural parts in heavy-duty vehicles. It is the same type of material that often is used within the aerospace industry. There are different types of fibres, continuous and short, and the first type will be considered.

1.5 Other studies and research

It is possible to reduce the weight for mass transit transport vehicles and heavy trucks with 40 to 60 per cent by changing from metal to composite material. The market is heavily under-utilised in terms of composites, because metal is the most used material today (Vaidya, 2011). Composite materials are used in other applications, one example is the airplane Boeing 747, where 50 per cent of the frame consists of CFRP, carbon fibre reinforced plastic. It is possible to save up to 30 per cent of the weight of conventional model by using CFRP instead of aluminium in the airplane structure (Hale, 2006). Other examples of the use of CFRP are the roof of the BMW M6 coupé (BMW AG, n.d.), and the front and fenders of the Chevrolet Corvette Z06. The front fenders in the Dodge Viper are also in CFRP, as well as the rear deck lid inner structure of the Ford GT (Sullivan, 2006). Lamborghini has produced the body of one of their cars, with exception for door and roof structure, entirely in carbon fibres reinforced epoxy. The weight has been reduced with 34 kg, approximately 40 per cent compared to its predecessor that had a body in aluminium (Feraboli & Masini, 2004). Carbon fibre composites are also used within military; the military boat the Swedish Visby Corvettes are made of composite materials (Kockums AB, 2012).

1.6 Disposition of thesis

Chapter 2, Issues with carbon fibre reinforced plastics, is part of the literature study, consisting of issues related to the manufacturing, processing and use of CFRP. The chapter is followed by the problem evaluation and selection of which issue to further investigate in chapter 3. Chapter 4, Fatigue, investigates what fatigue is and how it affects the composite materials. The fifth chapter, Method and materials, describes the procedure and methods used throughout the project. The results from the tests and the design guidelines together with information about the design process are presented in chapter 6, Results. The last chapters (7 & 8) include the discussion, conclusion and recommendations for future work.

2 Issues with carbon fibre reinforced plastics

Issues related to manufacturing, processing, usage and other aspects for carbon fibre reinforced plastics are described in this review. The issues are identified based on the background study about the material, manufacturing and processing, which all can be found in appendix A, Literature review. There are of course other problems than those mentioned in this review, some issues are without relevance for Scania and the heavy-duty vehicle industry and are therefore not considered. The one of the most promising material for this industry is CFRP with a thermosetting matrix, e.g. epoxy or vinyl ester. One reason for selecting thermosetting resins instead of thermoplastics is that the wettability and the viscosity is much lower for thermoset and it is therefore easier to impregnate the fibres. Thermosetting matrices, especially epoxy and vinyl ester have very good or equal properties compared to many other conventional materials, such as steel or aluminium. The properties of CFRP are in many aspects similar to steel, but with much lower weight. More about this is written, as mentioned above in the appendix.

2.1 Manufacturing

This section describes issues related to the manufacturing of composite materials. Information about the manufacturing processes can be found in appendix A.2 Manufacturing methods. The main issues are shrinkage and voids, but other problems such as difficulty to place the fibres and fibre breakage or fibre failure can occur.

2.1.1 Voids

Voids and porosity is one of the most critical problems during the manufacturing process (Campbell, 2010g) (Mallick, 2007c). The difference between voids and porosity is the size of the pores. A void is usually a large pore and porosity express a series of small pores, but in industry the terms are used interchangeably. Voids can occur either in the ply interfaces, or within the individual plies (Campbell, 2010g). The defects are commonly caused because the resin is not able to displace air from the fibre-resin interface when the fibres are coated with liquid resin. Voids can also occur if air bubbles and volatiles are entrapped in the resin. Large presence of voids can significantly reduce the tensile, compressive and structural strengths of the composite, but even small volumes of voids can significantly reduce the interlaminar shear strength of the composite. Another issue due to voids is the rising moisture adsorption in humid environment that generally can occur; this increases the physical dimensions of the part and reduces the matrix-dominated properties (Mallick, 2007c).

2.1.2 Shrinkage

Shrinkage is the reduction in volume or linear dimensions caused by curing and thermal contraction. This can occur during the curing process if polymer molecules rearrange into a more compact mass. Thermal shrinkage on the other hand occurs during the cooling period that follows the curing reaction, and can occur both inside and outside the mould. The shrinkage for vinyl ester and polyesters are five to twelve per cent, but can be significantly reduced by addition of low shrink activities. For epoxy the shrinking is one to five per cent. High resin shrinking eases the removal of the composite from the mould and can be desirable. It can however cause moulding defects, such as warpage and shrink marks (Mallick, 2007c).

2.2 Processing

Issues that can occur during or because of the processing of composites are considered in this section. Processing is in this project defined as the work done after the composite part is manufactured to give the part its final finish and size, and join several parts together.

2.2.1 Machining

Machining damage is inevitable if conventional material removal processes are used to machine composites. The damages can affect the mechanical properties of the composite. The quality of the machining is highly dependent of the cutting speed and the feed rate (Sheikh-Ahmad, et al., 2012).

Tool wear is one cause of machine damage to the composite part. It occurs when the cutting edge of the tool is deformed so that the initial cutting geometry is changed. Abrasion and micro chipping is the main reason why tool wear occur when machining fibre-reinforced plastics, FRP. The tool becomes less effective in material removal and in generating good quality machined surfaces. The cutting edge strength can be reduced, the tool forces and power consumption and the cutting temperature increase, the surface finish degrade, loss of part dimensional accuracy and possibility loss of productivity, can occur because of tool wear. It is therefore important to minimise and control tool wear (Sheikh-Ahmad, 2009c).

2.2.1.1 Delamination

Delamination is when the different layers in a laminate separate from each other (Nationalencyklopedin, 2013). It is a major issue when machining FRPs and a considerably amount of time and cost could be saved if delamination could be avoided. Delamination can proceed at different processes, for example milling (Hintze, et al., 2011) and drilling (Sheikh-Ahmad, 2009a). When machining FRPs is tool wear a major reason for the occurrence of delamination. A sharper tool decreases the risk for delamination, because the fibres are cut cleanly. The delamination is very marked, in form of fibre overhangs and fibre breakouts that occur on the top layers of the cut edges, when the tool has high wear (Hintze, et al., 2011). Delamination severely affects the structural integrity and long-term reliability of the machined component. It is the most serious limitation to machinability of drilling FRPs. Drilling operations are associated with a thrust force, which acts normal to the ply and tends to separate the layers in a laminate by interlaminate cracking or intralaminate cracking. Delamination during drilling can occur in two ways, by peeling up the top layer of the laminate or punching out of the uncut layer near exit, Figure 1. The top layer of the composite is peeled up when the thrust force is sharply decreased and mechanically peels up the work piece. Push-out is on the other hand associated with a tool that acts as a punch and separates the thin uncut layer from the remainder of the laminate. It is necessary to reduce or distribute the thrust force component to reduce delamination when drilling. There is a direct relationship between the extent of delamination and the feed rate. Knowledge is therefore necessary in order to select proper feed rates for avoiding delamination (Sheikh-Ahmad, 2009a). It can also occur when milling CFRPs, occurrence and propagation are two mechanisms of key importance for describing delamination. If it occurs when milling, the delamination is generally depending on the condition of the tool and the fibre-cutting angle on the laminate top layers (Hintze, et al., 2011).

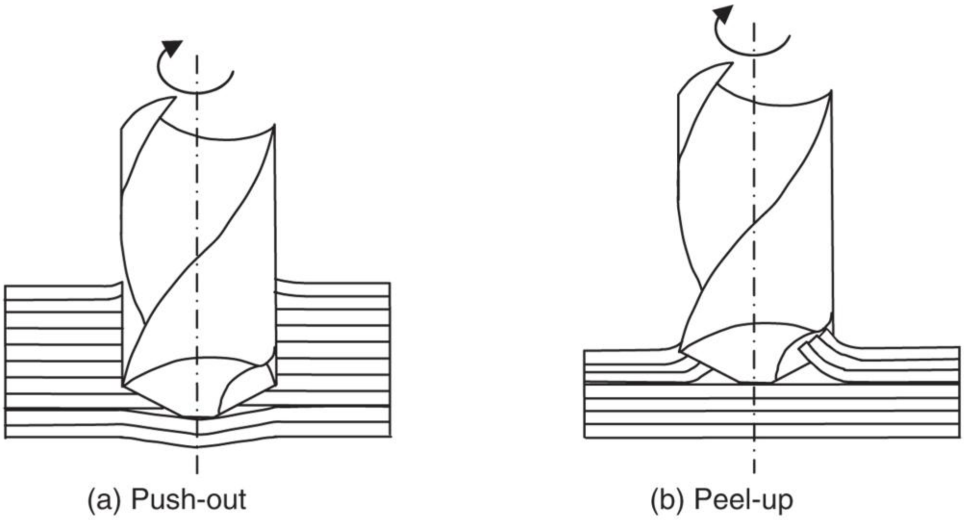

Figure 1. Delamination when drilling (Sheikh-Ahmad, 2009a, p. 198)

2.2.2 Joining

Composites can be joined in different ways, as described in appendix A.3.2 Joining. Mechanical fasteners, adhesive bonding and welding are often used. Welding is used for thermoplastics and problem regarding this is therefore not considered. This section has been divided in two sections dependent on the type of joint, mechanical fastener and adhesive bonding.

2.2.2.1 Mechanical fasteners

Bearing, net tension and shear-out are common among the possible joint failure modes that may occur in composites, this according to Nassar and Yang (2013) and Vaidya (2011). These problems occur because of compressive stress in the materials that are immediately close to the contracting bolt surface (Vaidya, 2011). Campbell (2010h) mentions bearing, tension, shear-out and cleavage tension as problems caused by mechanical joining. There are three types of fatigue damage around the bolt hole: hole wear, damage in the contact surface of the composite, and growth of delamination around the bolt hole caused by drilling (Nassar & Yang, 2013). Other problems related to the bolt hole are fastener pull-through and fastener failure (Campbell, 2010h). The joint geometry and laminate lay-up are primarily affecting the occurrence of failure modes, but the type of fastener can also affect the occurrence (Nassar & Yang, 2013). Cole, Bateh and Potter (1982) mentioned galvanic corrosion, galling, installation damage and low-pull strength as primary problems with fasteners.

Galvanic corrosion

Galvanic corrosion is one of the most common problems with CFRP and many fasteners (Cole, et al., 1982). A picture of the problem is shown in Figure 2. In this case black bolts coated with zinc and iron have been used in combination with CFRP and were placed in a salt spray chamber for 600 hours and have during this time corroded (Johansson, 2013). Galvanic corrosion is when a metal is degrading due to an electrochemical reaction with its environment (Tavakkolizadeh & Saadatmanesh, 2001). It is a result of different electrode potential between graphite/epoxy and metals (Cole, et al., 1982) and occurs if CFRP is placed next to an anodic metal, e.g. aluminium (Campbell, 2010b). Studies have been done to examine the possibility of galvanic corrosion for composites with graphite/vinyl ester and graphite/epoxy. Both composites were directly coupled with mild steel water. The vinyl ester-based composites were significant blistering after six months. The epoxy showed no signs of blistering due to the absence of glass tow or epoxy after the same time period. The galvanic coupling of graphite/epoxy composites and magnesium in seawater was examined in another study made by Sloan and Talbot in 1992. A decrease of 30 per cent in shear strength of the composite coupled with magnesium was observed after 140 days of exposure to seawater. Galvanic corrosion rate is directly related to the epoxy coating thickness. Applying a thin layer of epoxy to the fibres can decrease the galvanic corrosion rate in seawater; the thicker the layer is the better is the protection and the lower the risk for corrosion. Sizing agents can also decrease the galvanic corrosion rate of the carbon fibres (Tavakkolizadeh & Saadatmanesh, 2001). Galvanic corrosion can be expensive to repair, as it requires drilling of new holes and installation of an oversized fastener of an appropriate material. It can lead to serious structural failure but if the materials are carefully selected corrosion can be avoided. There is for example risk for galvanic corrosion when steel is combined with CFRP, while titanium is not affected by galvanic corrosion at all in combination of CFRP (Mueller, et al., 2007). It can also be avoided by coating the bolts with a protective coating. The issue with coating is when the coating has flawed galvanic corrosion is no longer possible to avoid. Galvanic corrosion could also be avoided by using a titanium sleeve as a separator, but humidity can provide a bridge around the sleeve and corrosion can occur (Cole, et al., 1982). Electrical insulation glass fibre can be bonded to all surfaces that have contact with the metal to avoid galvanic corrosion (Campbell, 2010c).

Figure 2. Galvanic corrosion on black screws coated with ZnFe on CFRP (Johansson, 2013)

Bearing

Bearing failure is characterised by localised damages, for example delamination and matrix cracking around the hole, see Figure 3. Buckling and kinking of the fibres followed by crushing of the matrix can be a result of localised compression loading caused by the fasteners (Campbell, 2010h). The diameter of the hole with clearance, laminate thickness, material and layer stack sequences, washer and clamping pressure are all factors that can have significant effect on the bolt bearing behaviour for a single-bolt composite joint. There are two types of bolt bearing, bearing strain and bearing stress. Bearing failure is often seen as the “accepted” mode, compared to net-tension and shear-out. This because bearing failure is not catastrophic (Campbell, 2010h) (Nassar & Yang, 2013). Bearing usually gives higher strength and a less brittle failure. The latter two types of failures should be avoided through proper design of the joint geometry and the material itself (Nassar & Yang, 2013). Campbell (2010h) points out the importance of not design according bearing because it is an “accepted” failure mode and it will result in less optimum joint strength.

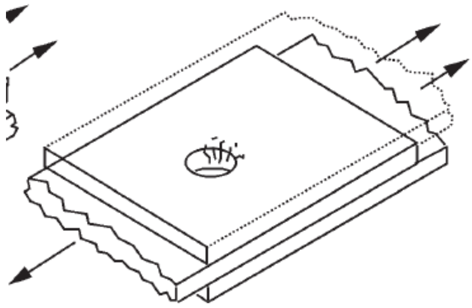

Figure 3. Bearing failure (Campbell, 2010h, p. 451)

Tension and cleavage tension

Tension failure can occur if the width is insufficient or if the plies oriented in the loading direction are too few, Figure 4 (Campbell, 2010h). Net-tension can be avoided by a proper design of the joint geometry and the material itself (Nassar & Yang, 2013). Cleavage tension failure occurs, due to insufficient distance and width to the edges, but also because of the number of cross plies is insufficient, Figure 5 (Campbell, 2010h).

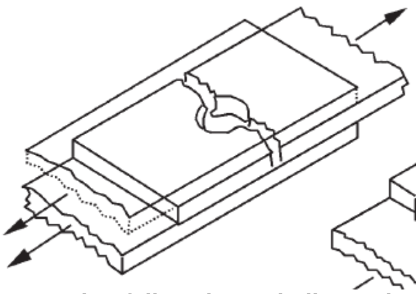

Figure 4. Tension failure (Campbell, 2010h, p. 451)

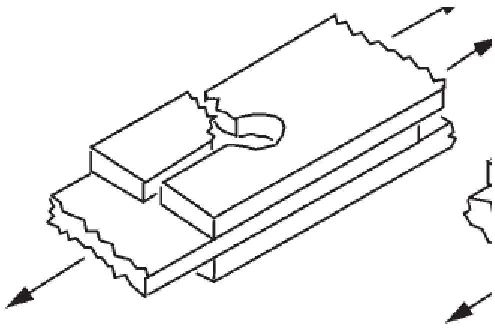

Figure 5. Cleavage tension (Campbell, 2010h, p. 451)

Shear-out

Shear-out failures is a result of insufficient distance to the edges or because too many plies are oriented in the load direction (Campbell, 2010h), Figure 6. It should be avoided in the same way as net tension, through proper design of material and joint (Nassar & Yang, 2013).

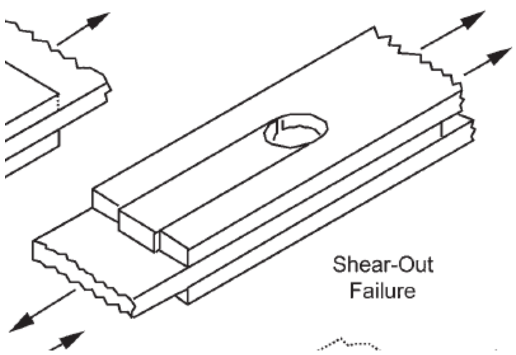

Figure 6. Shear-out failure (Campbell, 2010h, p. 451)

Problems with fasteners and around bolt holes

Fastener failure and fastener pull through are problems with fasteners that may occur. The fastener can fail if the fastener itself is not large enough for the laminate thickness and if there are unshimmed gaps or excessive shimmed gaps in the joint, or if there is insufficient fastener clamp-up (Campbell, 2010h). This is illustrated in Figure 7 below. Fastener pull-through can occur when the countersink is too deep or when shear head fasteners are used and causes damage in the laminate, Figure 8 (Campbell, 2010h).

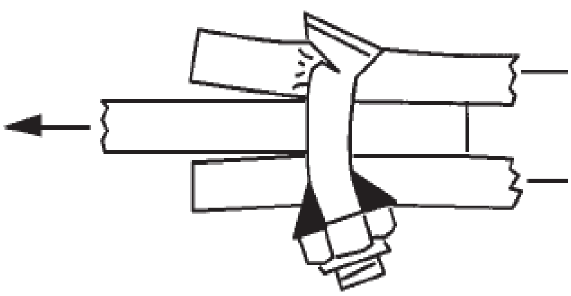

Figure 7. Fastener failure (Campbell, 2010h, p. 451)

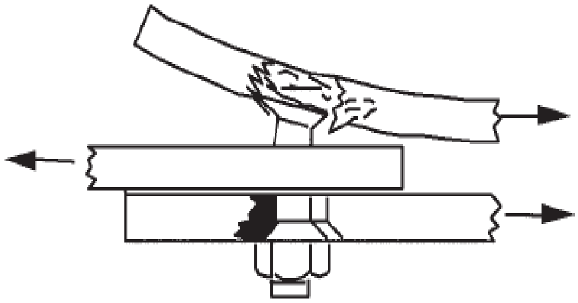

Figure 8. Fastener pull-through (Campbell, 2010h, p. 451)

Hole wear, damage in the contact surface and growth of delamination are damage modes that can rise around the bolt hole. When the friction force causes erosion of the material around the hole it is called hole wear. Damage in contact surface is caused by bolt bending under loading, which results in the hole elongation during fatigue loading. Growth of delamination and failure load can decrease the fatigue life of bolted joints (Nassar & Yang, 2013). Delamination is a common problem when machining composites, as described in section 2.2 Processing.

Problems caused by drilling

Drilling is mainly used for making holes for joining. These holes causes stress concentration in the composite joint plates, which can reduce the mechanical strength and the fatigue life of the structure. The probability for micro-cracks and local damages around the holes are increased when drilling, and these micro-cracks can cause structural instability (Nassar & Yang, 2013). Delamination, which is mentioned above, is another problem caused by drilling.

2.2.2.2 Adhesive bonding

Failure in adhesive bonding tends to start in the ply next to the adhesive, near the beginning of the joint or in the adhesive in the same area. In an adhesive with a low shear modulus and a high strain-to-failure the highest failure loads are achieved. The interlaminar shear failure of the bonded adherend or substrate layer can be minimised by ensuring that the surface fibres in a joint are parallel to the load direction. How efficient the joint can transfer loads is very much dependent on the design of the joint and as more complex the loading becomes the more complex the design of the joint becomes (Campbell, 2010h).

Adhesive creep

Adhesive creep is one factor that affects the long-term durability of the adhesive joints. The creep can be restricted by selecting long enough overlaps to produce a low-stress trough. The issue can occur both under cyclic and static loadings. When the load is removed there is no mechanism for the adhesive to return to its original state. The shear stress and strain is almost as high as the peak values at the end, if short joints are used. To push the adhesive back to its original position when the joints are unloaded stiff adherends can be used, so that the creep cannot accumulate. This prevents gross creep and is necessary in order to get a durable bonded structure (Campbell, 2010h).

Peel stress failure

Peel stress, Figure 9, occurs because of eccentricity in the load path. The failure can occur for single-lap joints but may also occur in double-lap joints, even if the latter can seem to be balanced. Peel stress can be avoided by modify the joint geometries, so that the tips of the composite are thin and flexible. Only negligible peel stress can occur in this way. The thickening of the composite has to be done carefully with high-flow elevated temperature curing, to prevent creation of voids. Additional adhesives or scrim fillers can also be used to prevent problems with voids. It is impossible to overdo the peel stress relief as long as the overlap is long enough. A natural fillet or spew can occur when the adhesive flows during cure, this should never be removed as tests have shown that it improves the joint's static and fatigue properties (Campbell, 2010h).

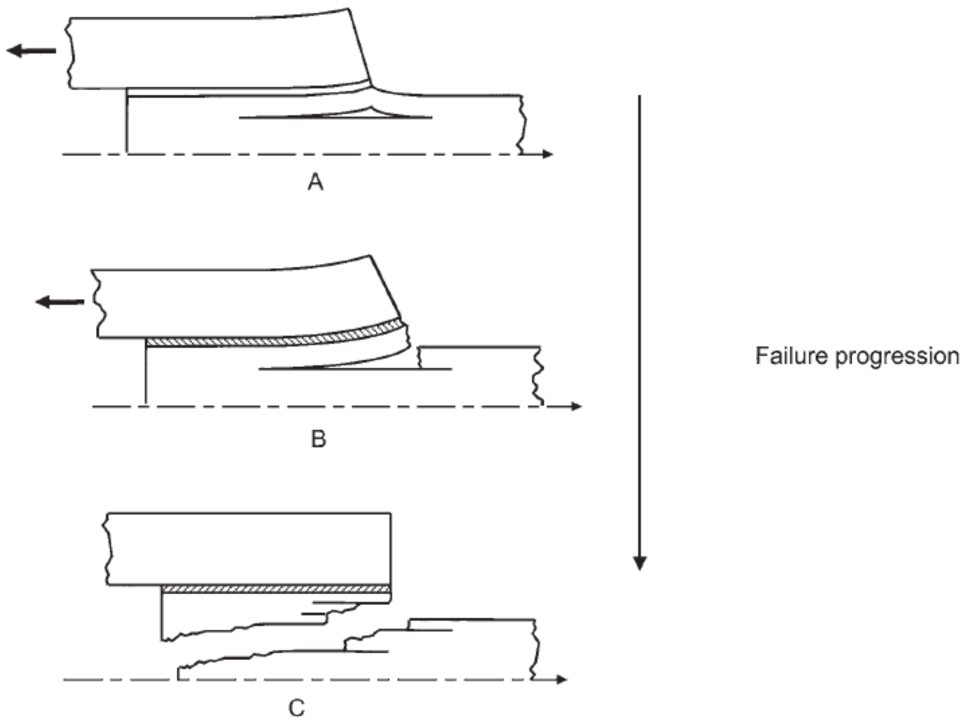

Figure 9. Peel stress failure (Campbell, 2010h, p. 480)

2.2.3 Surface treatment

Typical surface defects on painted CFRP are according to Souza, Mardel and Fox (2012): blistering, laminate distortion, loss of adhesion, softening, cracking, flaking, chemical separation, fibre exposure, orange peel and print through. The most common defects are orange peel and print through. Orange peel is when small dimples in the paint occur, like the peel of an orange. Print through is a surface defect on painted fibre reinforced composites. It is a result of variation in resin and fibre density beneath the painted surface. It can also occur if the composite is not fully cured before painting, and can result in permanent print through of the fibres (Souza, et al., 2012).

The automotive industry has issues with getting Class A surface finish on the composite components. Surface porosity and dry fibre voids are common problems. Those problems can usually be avoided through operator experience and optimisation of the curing process (Herring, et al., 2010).

2.3 Usage

This chapter describes problems that may occur during usage. The problems are related to the use of composite materials in structural parts. Two of the most common ones are damp, and fatigue, which may occur when the composite is used in a structural part.

2.3.1 Damp

Damp is affecting the fibres and the matrix in different ways, the hot/wet behaviour of the matrix and the fibres are totally different. The fibres show no diffusion of humidity while the matrix is absorbing water. The diffusion coefficient is depending on temperature and the mechanical and physical properties can therefore change, due to higher temperature and physical properties. The mechanical properties of the composite are affected in the following ways:

- The matrix stiffness and strength is reduced.
- The interlaminar shear strength is reduced.
- Reduction of glass transition temperature T_g.
- The viscoelastic properties and damping behaviour increased.

Such polymer properties can be detected with a thermo analysis. Degradation due to moisture and media are normally less severe than corrosion of metal structures (Drechsler, et al., 2009).

2.3.2 Fatigue

Fatigue is the weakening of the material that occurs when the material is exposed to cyclic loading, which leads to cracks and damages in the material after a number of loadings (Johannesson & Liedholm, 2013). In comparison to homogenous and isotropic material with the same behaviour in all directions, the damage characteristics for polymer matrix composites, PMC, are much more complex. The reason for this is because the material and laminates are inhomogeneous and anisotropic. Damages related to fatigue starts in the plies where the fibre orientation is different from the loading direction, and begins with initiation, growth and propagation of micro-cracks in the polymer matrix. These cracks extend across the ply thickness. As a result of these cracks the fibre starts to break and to separate the matrix from the fibres near the fibre ends. Perpendicular to the first cracks occur secondary matrix cracks, with restricted length. The damage continues until a characteristic state of crack saturation is reached, this type of degrading of the material weaknesses the laminate. The laminate fails by fibre breakage in those plies due to increased stresses and strength degradation. In Figure 10 a schematic picture of fatigue strength relative the ultimate strength for CFRP, glass fibre reinforced plastic (GFRP), aluminium, and steel, can be seen. In general CFRP are essentially insensitive to cyclic loading (Drechsler, et al., 2009).

Fatigue tests are done in order to evaluate how many times a material can be loaded with a certain load before it breaks (Nationalencyklopedin, 2013). Three-point bending, four-point bending and cantilever bending are all different bending tests for evaluating fatigue of composite (Couillard & Schwartz, 1997).

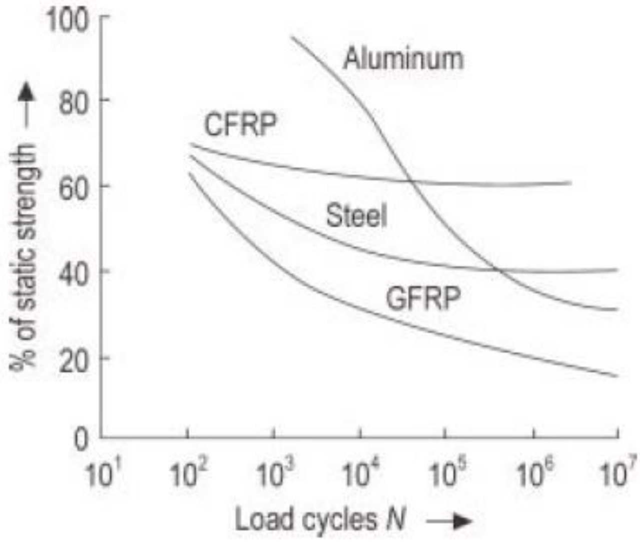

Figure 10. Fatigue strength relative the ultimate strength for some structural materials (Drechsler, et al., 2009, p. 19)

2.4 Other problems and aspects

Problems that are not categorised within manufacturing, processing or usage are described in this section.

2.4.1 Damage impact

Low velocity impact damage in laminated composite structures can weaken the material. This type of damage can occur due to low velocity e.g. a dropped tool or other manufacturing or handling accidents. This is especially damaging for carbon fibre epoxy composites that are used within high performance vehicles, e.g. in aerospace. This because both the fibres and the matrix are elastic and brittle, compared to metals. The damages can be a mixture of internal lamination or back-face tension driven failure. Back-tension driven failure will initially be matrix cracking or splitting between fibres, and if the bending strains are high enough the fibres will then fracture and further delamination occur. These types of damage models are extremely weakening, mainly due to the compression strength of the structure. When they are viewed from the external impacted surface they can be completely invisible. Those barely visible impact damages are a hidden threat (Davies & Zhang, 1995).

2.4.2 Design considerations

It is not possible to construct products in the same way for composite material as for metals, and composites require specialist knowledge of both the material and the related process. The opinions whether designers have enough knowledge or not differs. According to Mangino et al. (2007) have automotive designers today an understanding of how to design in composite materials. The authors mean that there is a lack of adequate simulation software for all design phases. Weber (2010) has interviewed different persons within the industry, and many of them on the other hand believed that there is a lack of knowledge regarding composites. They mean that people need to learn more about what composite materials are and how they behave, as the personal definition of what composites really are differs (Weber, 2010).

A vehicle’s crashworthiness is an important aspect in automotive industry. If composites are properly designed the material can offer excellent crash performance, and the specific energy absorptions are better than for metals. The material's crash performance is expensive to test, especially in full-scale, as it requires very specialised equipment and the structure cannot be reused after testing. There are data programs for these kinds of simulations, but there is a lack of reliable data properties for composite materials. It can take very long time to simulate crashworthiness, and this is the problem rather than lack of material with the right properties (Mangino, et al., 2007).

2.4.3 Health aspects

The use of thermoset material can affect the health of the persons working with the material. The Swedish Work Environment Authority has set up regulations and restrictions of how thermoset matrices are allowed to be handled in order to reduce those risks. The persons handling the material have to be educated in hazards and necessary precautions with the work. There are also requirements on the equipment in order to prevent air contaminations. The persons working with thermosetting plastics also have to go through medical examinations. Generally there are no health risks with completely cured thermosetting plastics at normal usage. However, certain residues of thermosetting plastics component may persist in the cured composite and can in rare cases cause eczema for those that already are sensitising. Many products used within manufacturing of materials in thermosetting components, can cause health problems. Powerful skin-allergies may occur because of some resins, (e.g. epoxy, phenol and acrylic) and many components in the hardeners can cause skin allergies. The hardeners can also cause irritation to the skin, respiratory tract and to the eyes. Hypersensitivity redactions in the respiratory tract may also be caused of hardeners and aromatic amines can be carcinogenic and skin-sensitising (Swedish Work Environment Authority, 2005).

3 Evaluation of problems

Based on chapter 2, Issues with carbon fibre reinforced plastics, the following four problems have been identified as the most critical issues when using and manufacturing structural parts in composites for heavy-duty vehicles:

- Joining
- Delamination
- Fatigue
- Galvanic corrosion

Joining

There are many problems related to joining two parts together, which type of problems that may occur are however dependent on the type of joint. Stresses around the bolt holes, galvanic corrosion and delamination are issues related to mechanical joints. In order to be able to use bolts it is necessary to drill holes, and delamination may then be an issue. In the interface between the carbon fibre composite and the bolt, there is a risk for galvanic corrosion, depending on the material in the bolts. There are other problems related to adhesive bonding, creep and delamination may be problem for this type of joint. The design of the bonding is very important to ensure that the loads are efficiently transferred within the joint.

Delamination

When the different layers in a composite are separated from each other it is called delamination and it is one of the most common reasons for fibre failure. It is a large problem as the material's properties are affected because the fibres are damaged. It is possible to reduce the problems by changing the feed rate of the tool when machining, e.g. drilling. It can also somewhat be avoided by selecting a different machining process, such as water jet.

Fatigue

Fatigue occurs when the material is exposed to cyclic loading and breaks due to this. There is a risk that the fibres break and the material's properties lost if the loading is too high. Knowledge about fatigue of CFRP and the probability that it occur for CFRP is relatively low at Scania, as the material is not used today and the field is relatively new within the vehicle industry.

Galvanic corrosion

When a metal and carbon fibres are bonded together, there is a risk for corrosion on the metal due to different electronic potential in the materials. The metal is degrading and the joining may fracture. Galvanic corrosion is a problem because the joint between the metal and composite material risks breaking due to corrosion on the metal that decreases the mechanical strength and changes the properties of the material. The link is in this way becoming the weakest link. This problem will not occur for all metals, and by changing the material to one that does not corrode in contact with carbon fibres this can be avoided. Surface finishes can also be used to avoid direct contact in the interfaces.

Focus area

This project focuses upon these identified issues, and how they affect the designing of composite structures. Fatigue is used as design parameter when designing structural components in steel at Scania, and it was therefore assumed that this parameter should be used when designing in CFRP too, it was however not known if it actually was this way. A deeper investigation of fatigue was therefore done, which is following this chapter. The main reason for doing this investigation was to better understand the underlying reasons for fatigue, and whether it is an issue or not. Description and discussion of how to handle all four issues were however included in the design guidelines.

4 Fatigue

The fatigue behaviour of composite material was deeper examined and resulted in the following chapter. It is divided into two sections, general understanding that includes information about fatigue in a relatively broad perspective; the second section, deeper understanding, considers the material behaviour and other factors that may affect the composite. These two sections are followed by a short summary.

4.1 General understanding

This section describes the basics of fatigue, what it is, how and why it occurs and how to avoid or predict fatigue. The main focus lies on continuous carbon/epoxy composites, preferably multidirectional but carbon/plastic or fibre/plastic composites are mentioned if no relevant information can be found for the specific case.

4.1.1 What is fatigue?

Fatigue is the weakening of the material that occurs when the material is exposed to cyclic loading, and leads to cracks and damages in the material after a number of loadings (Johannesson & Liedholm, 2013). Composite materials are designed to be insensitive to fatigue, but they still suffer from fatigue loads. One reason among others is because the failure of composites is sudden and without prior notice, it is therefore important to understand and to predict the fatigue life of composites (Vassilopoulos & Keller, 2011b). The fatigue life is the number of cycles of alternating stress that is required to cause failure to the test specimen (Gooch, 2007d). The majority of important structures, for example aircrafts and other vehicles are committed to cyclic loading during usage (Tomita, et al., 2001) and fatigue is one of the main reasons for failure in many structural materials, also for CFRP (Khan, et al., 2010). The fatigue resistance of CFRP is good, and the material has virtually an unlimited life under fatigue loading (Chung, 2004). The fatigue strength is much higher relative to its static or residual strength and the static or residual strength requirement is typically much higher than the fatigue requirement, composites are therefore usually not fatigue critical (Campbell, 2010c). The fatigue properties of carbon fibre composites are superior to all known metals, when the fibres are reinforced with a proper resin (Walsh, 2001), and as long as reasonable strain levels are used during design should fatigue not be a problem (Campbell, 2010c).

Even though fatigue of composites can appear very early during fatigue testing, composites can last for very long periods before fracture takes place (Tai, et al., 1999). Fatigue can become a problem when composite materials are replacing traditional used materials, such as steel, aluminium or in structural components that have to bear large fatigue loads during operation. The sensitivity for fatigue of each structure then changes. A road bridge in concrete is for example normally not sensitive to fatigue, as the dead loads are much higher than the live loads. If a lightweight material instead is used this may no longer be the case and fatigue becomes an issue (Vassilopoulos & Keller, 2011b).

4.1.2 How fatigue occurs

Fatigue and related phenomena are the most common causes of structural failures in engineering structures and must therefore be considered in any design process (Vassilopoulos & Keller, 2011b). In composites it generally occurs because of damage accumulation (Weber & Schwartz, 2001) caused by interaction between different damage modes, such as delamination, matrix failure, fibre pull-out or fibre fracture (Vassilopoulos & Keller, 2011b). Failure of composites due to fatigue is because of this more difficult to predict than for failure due to fatigue in metals (Weber & Schwartz, 2001). The failure of fibre-reinforced plastics is neither dominated by a single crack nor increments the same way as is common for metals (Vassilopoulos & Keller, 2011b). Failure due to fatigue starts according to Drechsler et al. (2009) in the plies, where the fibre orientation is different from the loading direction, and begins with initiation, growth and propagation of micro-cracks in the polymer matrix. These cracks extend across the ply thickness and as a result of the cracks the fibre starts to break and the matrix separate from the fibres near the fibre ends. Perpendicular to the first cracks occur secondary matrix cracks that stays restricted length. Until a characteristic state of crack saturation is reached the damage continues. This type of degrading weakens the laminate and the laminate fail by fibre breakage in those plies due to increased stresses and strength degradation (Drechsler, et al., 2009). The weak links of the components commonly laminates and joints, that transfers loads from one part to another, are mainly affected by fatigue. The structural integrity of those parts is therefore very important for the whole system's viability (Vassilopoulos & Nijssen, 2010).

One reason why fatigue occurs is the rise of defects in the material during the manufacturing process. Wrinkles, fibre misalignments, and voids are such defects (Vassilopoulos & Keller, 2011b). These defects can act as sites for fatigue failure (Couillard & Schwartz, 1997) and are potential damage points that fast can develop into failure mechanisms, for example matrix cracking, fibre breakage, debonding, transverse-ply cracking, or interface cracking. These failure mechanisms can occur both independently or interactively and are the reason of micro-buckling, translaminar crack growth and delaminations, which can cause failure of the composite (Vassilopoulos & Keller, 2011b).

Fatigue damage in CFRPs is very complicated (Khan, et al., 2010) (Tomita, et al., 2001) and the damage states are closely related to the material's anisotropy and heterogeneity. It is gradually degrading the mechanical and structural properties of the composite and leads to formation of different stress levels depending on the lay-up sequence and orientation of laminate (Khan, et al., 2010). This is the same for all composites; the stress within a composite material can vary depending on the inhomogeneous structure (Couillard & Schwartz, 1997).

Fibre failure, interfacial debonding, delamination and matrix cracking (Couillard & Schwartz, 1997) (Tomita, et al., 2001) are common damages during fatigue failure of multidirectional laminates. The matrix cracks are dependent on the stress levels, and initially appear in one layer. The cracks can be transferred to close layers under high stress levels, or stay restricted in the initial layer under low stresses and can develop parallel to the transverse loading. These types of matrix cracks can cause delamination or fibre fractures. When the layers delaminate they act independently and not as a part of the multidirectional laminate. The reason for this is because interlaminar stresses develop and lead to delamination of adjacent layers. It occurs also because the strain fields developed in the laminate do not allow all layers to comply with the strain capability equations. One type of interfacial failure is crack propagation in the small region between the matrix and the fibres where they are connected by mechanical and chemical bonds. Fibre fracture is usually the last stage of damage accumulation in fibre composite materials. Fibre failure occurs in most cases when the matrix already is damaged and unable to transfer any loads (Vassilopoulos & Keller, 2011a). Fibre failure generally proceeds through the distribution of damage at cross-sections of the material (Couillard & Schwartz, 1997). Failure mode of multidirectional laminates is containing all the mentioned failure modes to some extent: matrix crack, layer delamination, interfacial failure and fibre fraction, and is mainly dependent on the stacking sequence and loading type. It can be difficult to identify the reason for failure in multidirectional laminates and to identify the dominant mode. This because even though the failures can be recognised independently of each other, they act synergistically and appear simultaneously at different locations in the loaded material. Different methods can be used to observe the damages, e.g. x-ray, acoustic emission, reflected light microscopy, surface observation under fatigue loads, ultrasounds and, C-scan. It is relatively easy to identify damage mechanisms that are trigged during fatigue loads thanks to these methods, but it is difficult to model the interaction between different failure modes and to predict the consequences (Vassilopoulos & Keller, 2011a). The sudden degradation rule and gradual degradation rule is other ways to describe the degrading of the material properties due to fatigue. The sudden degradation rule is when the matrix or fibres fails based on the failure criteria, the properties suddenly decrease to an appropriate value and the part that fails is no longer able to carry the load. The gradual degradation rule is based on the composites stiffness and strength that gradually is reduced because of cyclic loading (Naderi & Maligno, 2012).

The fatigue behaviour of a unidirectional composite applied to tension-tension loading in the fibre direction can be described by a fatigue life diagram as illustrated in Figure 11. In this case a load-controlled test was used, and the vertical axis of the diagram is the maximum strain attained at the first application of maximum stress. The upper and lower limit to the fatigue behaviour is formed by the reference to the loading condition, formed by the quantity from the maximum stress. The strain to failure forms the upper limit and the lower limit is formed by the strain corresponding to the fatigue limit. Three failing regions can be viewed in the diagram. The first region is the horizontally extending scatter band where the probability of failure is between 5 and 95 per cent of the composite failure strain. Here is the lack of degradation strength, failure strain, represented. The second region, region II is the fatigue-life-scatter band and derivate from region I at a certain numbers of cycles and extends down to the fatigue limit. The region is controlled by the progressive mechanism of fibre-brigade matrix cracking. In the third region occurs no failure if the strain is below the fatigue limit, at large number of selected cycles (Talreja & Singh, 2012).

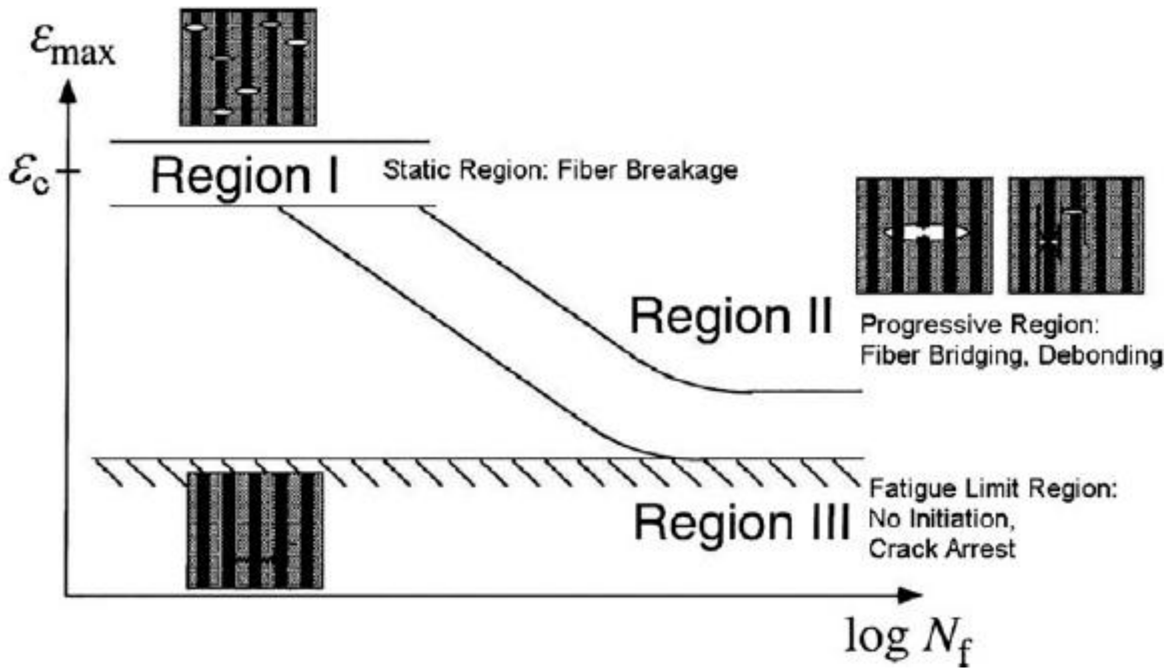

Figure 11. Fatigue life diagram for a unidirectional composite applied to tensile fatigue loading in the fibre directions that shows three regions with different damage mechanics (Talreja & Singh, 2012, p. 7.2)

The fatigue response could be divided into three life ranges according to Dharan. In the first region, up to 200 cycles, a small dependence of the fatigue life under cycling can be observed where the behaviour is dependent on the fibre mean strength and strength distribution. Fatigue in the second region, between 200 to 10^6 cycles, occurs by the growth of matrix micro-cracks that leads to preferential fibre failure, followed by interfacial shear failure. The applied stress is in the third region, more than 10^6 cycles, below the micro-crack initiation stress and no failure is expected (Razvan & Reifsnider, 1991).

4.1.2.1 Comparison to metals

The damage characteristics for polymer matrix composites are much more complex than for metals (Drechsler, et al., 2009) (Tai, et al., 1999) and other homogenous and isotropic materials with the same behaviour in all directions. The reason for this is because composites and laminates are much more complex and because composites based on polymers are inhomogeneous and anisotropic (Drechsler, et al., 2009). Failure of fibre-reinforced plastic, FRP, is not dominated by a single crack or increments in the same way as is common for metals, according to Vassilopoulos and Keller (2011b). Couillard and Schwartz (1997) on the other hand mean that fatigue both for metals and polymeric materials starts and increment by the growth of cracks. The fatigue properties of carbon fibre composites are superior to all known metals (Campbell, 2010b) (Walsh, 2001), when the fibres are reinforced with proper resins (Walsh, 2001). A comparison of the normalised notched specimen fatigue response of carbon/epoxy and some metals used for aerospace applications can be found in Figure 12. The strength in relation to density is much higher for the carbon/epoxy composite than any of the other materials. The fatigue behaviour is also different for the composite compared to the metals, the metals' fatigue strength in relation to density are degrading much faster under high cycles (Campbell, 2010b). CFRP has good fatigue resistance, and virtually has an unlimited life under fatigue loading according to Chung (2004).

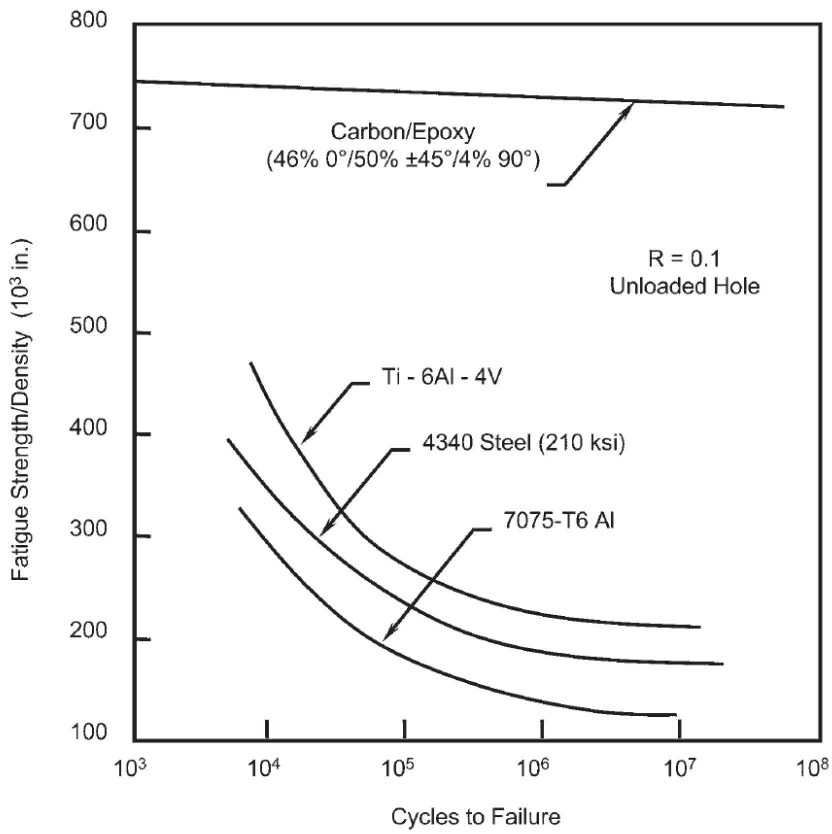

Figure 12. Fatigue resistance for some aerospace material (Campbell, 2010c, p. 16)

4.1.3 Avoiding fatigue

Extensional investigations of the fatigue behaviour for CRFP have been done over the last 40 years, as the material is used within the aerospace industry. The studies have addressed most aspects of fatigue-related problems, such as life prediction, property degradation, joint design etc. These studies have led to adaption of allowables and large amounts of data have been published

(Vassilopoulos & Keller, 2011a). One of the most important topics in composite research is assurance of structural reliability based on damage tolerance (Tomita, et al., 2001). It is also damage tolerance issues that have not been efficiently dealt with and the main reason for this is the lack of a generalised damage metric, such as the crack length in metals that could be used with different lay-ups and material configurations. Only limited research has been done about the effect of variable amplitude loading on the remaining life and fatigue behaviour of composite materials under complex stress states (Vassilopoulos & Keller, 2011a). Quaresimin and Talreja (2010) mean that there is a need for more research for better characterisation and understanding of how damage mechanisms act under cyclic multiaxial loading, and for their incorporation into reliable predictive models for general validity (Quaresimin & Talreja, 2010).

4.1.3.1 Predicting fatigue

It is difficult to get a general approach of the fatigue life for composite materials as there are many factors that differs between the materials, e.g. the fibres, matrix, lamination stacking sequence, manufacturing method, etc. It is neither possible to use the same methods for modelling and for predicting fatigue life for composites as for metals and conventional materials. The reason for this is the different fatigue behaviour for metals and composites (Vassilopoulos & Keller, 2011b); see Comparison to metals in section 4.1.2 How fatigue occurs. Fatigue becomes even more difficult to predict for composites when other factors, such as temperature (Vassilopoulos & Keller, 2011b) and thickness of the laminate (Tai, et al., 1999) are affecting the behaviour. The validity for fibre-reinforced plastics is questionable and the fatigue design is difficult to calculate. This mainly because of the lack of a reliable nonlinear damage accumulation rule and because the knowledge of fatigue properties of specific FRP laminates are limited, especially for high cycle levels, e.g. 10^8 to 10^9 cycles (Vassilopoulos, 2010). There are few studies that examine fatigue behaviour up to 10^9 cycles, and as far as Michel et al. (2006) know their study is the first. There is also limited data available for cycles beyond $5×10^6$ and one reason for this could be that it is very time consuming to test fatigue with more than 10^6 cycles (Michel, et al., 2006). Even if there are methods for predicting fatigue is the issue with many of them that they are designed for a specific material under a specific loading. There was no widely accepted method in 2010 that could guarantee lifetime estimation, accurate for any composite material system, component or structure under variable amplitude loading (Vassilopoulos, 2010).

In order to develop a method for accurately predict the fatigue life for composites under variable loading it is necessary to have an understanding and quantification of both the effect of alternating and mean stresses under constant amplitude loading, as well as of the effect in variation in alternating and mean stressed on the fatigue life. A large amount of fatigue testing for different types of cyclic loading conditions are required to evaluate the effect of loading mode on the sensitivity to fatigue of composites, which is both time and cost consuming (Kawai, 2010). During the last decades very comprehensive databases have been constructed and numerous experimental programs have been realised. Some of the databases refer to specific materials and the main reason for determining the data have been to assist the development of a theoretical model. Other databases cover a wider range for specific applications. Other theoretical models have been developed to model the fatigue behaviour of examined composites and consequently predict their behaviour under unknown loading conditions (Vassilopoulos, 2010). If fatigue data is available the fatigue model is established in terms of a mathematical expression, and the parameters in the model are estimated by fitting the experimental data (Vassilopoulos, et al., 2008).

Fatigue failure criteria formulated on the basis of global stresses have little chance to succeed in predicting fatigue life for other materials than the specific laminate that are under consideration. This because the damage mechanisms responsible for fatigue failure occur locally and are driven by the local stress fields. The produced local stress states are depending on the stacking sequence and will generally be different for the same external multiaxial loads (Quaresimin & Talreja, 2010).

Vassilopoulos (2010) classifies theoretical models for fatigue behaviour in to two major categories. The first category includes theories based on macroscopic failure criteria and theoretical formulas to predict life under constant or variable amplitude loading. Experimental observations of damage mechanisms and their development during fatigue are not considered in those theories. S-N curves, computational models are examples of theories fitting in this category. Theories in the second group are based on actual damage measurements during fatigue life, but a damage metric is used as an indicator of damage accumulation. These theories can be divided into sub-categories according to the metric: strength degradation fatigue theories, stiffness degradation fatigue theories, and actual damage mechanism fatigue theories (Vassilopoulos, 2010). Nyman (1996) suggested a method for predicting fatigue life by using the Tsai-Hill criterion in his study about designing for fatigue. Vassilopoulos (2010) mean that Nyman's simplified method to derive fatigue curves by using a Tsai-Hill criterion has been proved to be inaccurate because one of the steps was inaccurate. There are several other methods for fatigue life prediction that have had the same problem as Nyman (Vassilopoulos, 2010). A few methods are briefly described below, but as mentioned earlier the main issue with predicting fatigue behaviour is the lack of available data for the specific material and loadings. Other methods are Tsai-Wu criterion modified for cyclic loadings that can be used to predict fatigue strength of multidirectional laminates under different loading directions, the Hashin model that was validated on fatigue data for off-axis, cross-ply and pin-loaded laminates. Strain energy based models can be used for describing the off-axis fatigue behaviour of composite laminates (Quaresimin & Talreja, 2010).

Computational methods

Computational methods, such as adapted neuro-fuzzy inference systems and genetic programming, have within the last years been introduced for modelling the fatigue life of composites. These tools are powerful for modelling nonlinear behaviour of composites subjected to cyclic constant amplitude loading. The tools can be used to model fatigue life for several composite systems and can favourable be compared to many other modelling methods (Vassilopoulos, 2010).

Finite element analysis is one way to perform the design analysis and may be necessary to use for complex structures and loadings. The analysis following the same procedure for both metallic and composite materials, but for composite materials with preparing the input data and interpreting the output data it is much more complex. The material specification should for composites include the fibre orientation angle in each layer, the thickness of the layer and the location of each layer in respect to the element mid-plane. Basic material properties are also needed. The stress output for a composite can be very large as it contains three in-plane stresses in each individual layer as well as the interlaminar stresses between the different layers (Mallick, 2007a). Finite element simulations are well suited to predict fatigue life of 2D composite materials. Naderi and Maligno (2012) used a 2D finite element method in order to predict fatigue life of carbon epoxy composites and the actual result and the predicted are well agreeing of the fatigue life. Delamination was however neglected in this investigation (Naderi & Maligno, 2012).

S-N curves

S-N curves are one way to visualise experimental fatigue data and to express the relationship between fatigue stress and fatigue. There are several models for these curves, depending on test situation and material (Tai, et al., 1999). The curves were traditionally used for describing the fatigue behaviour for metals, but were initially adapted for uniaxial loaded composites. The data in the S-N curves is commonly fitted by a semi-logarithmic or logarithmic curve. The best curve is the one that fits the fatigue data for the specific material, but such curve can be difficult to find, as there is no rules for this process (Vassilopoulos, 2010). S-N curves do not take different stress ratios or frequencies into account, and different parameters have to be considered for different loading conditions. The curves are case sensitive and the result can be accurate for one loading condition or system but poor for another (Vassilopoulos, et al., 2008).

Residual strength and stiffness

The degree of damage in a polymer matrix composite can be followed by study the decrease of a relevant damage metric, usually the residual strength or stiffness. Theories based on residual strength degradation assume that damage is accumulated in the composite and failure occurs when the residual strength decreases to the maximum applied cyclic stress. There are weaknesses with the methods and trials to overcome these weaknesses have been done and involve metrics that can be measured using non-destructive techniques e.g. stiffness degradation. During the fatigue life are stiffness changes usually greater than residual strength changes (Vassilopoulos & Keller, 2011b).

Methods for metals

Nakada et al. al (2007) and Noda et al. (2007) examined if two traditional methods for metals could be used for composite materials. Nakada et al. (2007) studied if the linear cumulative damage (LCD) rule with statistic approach could be applied for composite materials. A CFRP laminate consisting of carbon fibres and epoxy was tested with a three-point bending test under various cyclic loading with constant and variable stress amplitude and frequency. The authors draw the conclusion that the LCD rule was applicable for this fatigue life under variable cyclic loading and the specific CFRP laminates (Nakada, et al., 2007). A similar study was done by Noda et al. (2007) to investigate if the statistical linear cumulative damage (SLCD) rule could be used for composites. Two kind of epoxy based CFRP laminate were examined, one of them plain woven and the other a quasi-isotropic laminate. Three-point bending tests was performed and from the statistic viewpoint was it possible to confirm the applicability of the SLCD rule to the flexural fatigue life of the used CFRP laminates for the variable frequency as well as variable amplitude (Noda, et al., 2007).

Mathematical models

Mathematical models were developed to analytical describe fatigue damage and predict the fatigue lifetime of composite materials. The models were at the beginning based on earlier experience of fatigue life prediction for metals, and similar measurable material characteristics were selected for the specific case to form the fatigue damage metric. The damage in the material was measured, based on the degradation quantity with loading cycles. Different damage metrics have been used to measure fatigue damage accumulation, with the aim to establish a process that requires a minimum of experimental data and reliably predict the material’s condition (Vassilopoulos, 2010). This type of models is often very simplified in comparison to real structures and was created on the basis of testing results of specific specimens. All mathematical models give an approximate result, and it is therefore no point in selecting a very sophisticated model (Rodzewicz, 2010).

4.1.3.2 Testing

Fatigue tests are done in order to evaluate how many times a material can be loaded with a certain load before it fails (Nationalencyklopedin, 2013). Three-point bending, four-point bending and cantilever bending can be used to evaluate and examine the bending fatigue behaviour of composite materials (Couillard & Schwartz, 1997). Many parameters affect the material behaviour when testing fatigue: the loading pattern, control mode, stress ratio, testing frequency/strain rate, waveform, and testing temperature. Different loading types are: uniaxial, block, variable amplitude, and multiaxial. Block loading, variable amplitude loading and multiaxial loading are used in experiments to test more complex loadings. Block loading is used to test sequence effect on the composite’s fatigue life. Variable amplitude loading is used to test the material behaviour under realistic loading conditions and the material behaviour under complex stress is tested by multiaxial loadings. Stress ratio concerns different types of loading, composite material behave differently depending on if it is compressing or tension loadings. The stress ratio is the ratio between the minimum and the maximum amplitude loading. The frequency is a limiting factor in fatigue testing of composite materials, and the fatigue life of composite materials is considerably affected by the testing frequency, in contrast to metals. Which shape the applied waveform has can also affect the fatigue behaviour, and the sinusoidal is the most commonly used. Higher testing temperatures are in general decreasing the fatigue and static strength of the composite material (Vassilopoulos, 2010).

4.1.4 Different fatigue loadings

Composites are behaving differently depending on the type of loading applied to the material. The mode of loading is affecting the degradation of fatigue (Hartwig, et al., 1998):

- Threshold tension or threshold compression
- Tension-compression
- Shear or torsion
- Bending

The main modes of damages, when the loads exceed the critical limits can be seen in Figure 13 (Gay, et al., 2002). The figure shows how different loadings affect and damages the composite.

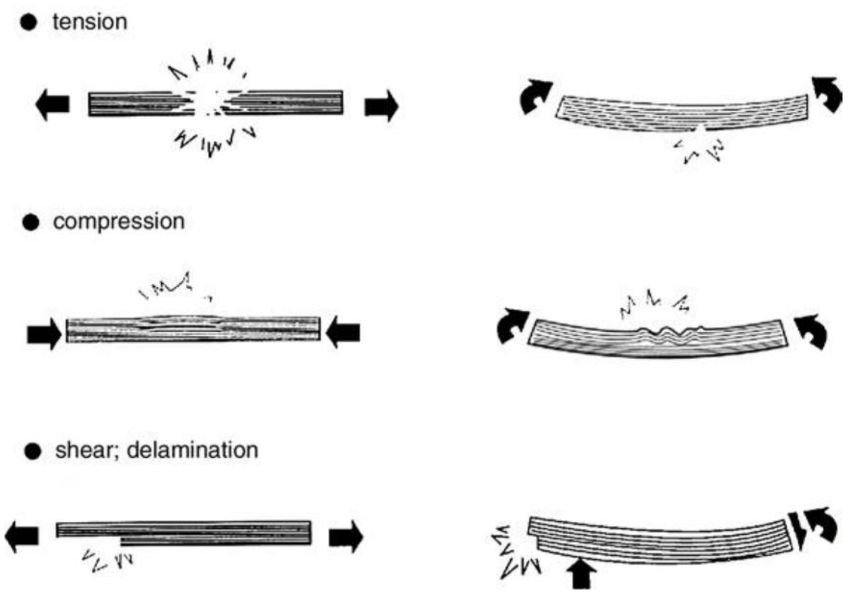

Figure 13. Damage modes due to different loadings (Gay, et al., 2002, p. 5.3.1)

Couillard and Schwartz (1997) studied the bending fatigue behaviour of carbon fibre composite materials. They mean that the a unidirectional composite will fail when the fibres reach their compressive strength or the fibres may buckle and fail in bending if the material is loaded in compression. Under compressive loading is the compressive strength and the endurance stress just about half of the corresponding tensile values (Couillard & Schwartz, 1997).

Composite materials have poor transverse strength and are sensitive to micro-cracks induced in the matrix. The formation of micro-cracks differs between the matrices, as well as the fatigue endurance limit (Hartwig, et al., 1998). The specimen will withstand cyclic stress, if the applied stress is below the fatigue limit (Gooch, 2007d), which for epoxy is 0.6 per cent strain. The repeated stress required to cause failure by fatigue decreases generally when the number of cycles increases (Couillard & Schwartz, 1997).

Multiaxial loading, such as tension-torsion loading reduces the modulus and the fatigue behaviour drastically and alternating loading leads to a shorter fatigue life than for threshold cycling. Carbon fibres have the highest tensile strength in comparison to Kevlar, glass and ceramics under the same conditions. If tensile loading is applied to unidirectional fibres, carbon fibres have higher strength, compared to glass, Kevlar and ceramics, if the same matrix is used. As long as no modulus degradation occurs during fatigue cycling the strain is the appropriate parameter instead of stress for unidirectional composites where the matrix and fibres are loaded in parallel. According to Hartwig et al. (1998) have separate investigations shown that the modulus is nearly unchanged until fracture occurs. The shear stress for composites with the fibre orientation ±45° can be divided into tensile and compressive stress along the +45° and -45° directions respectively. Half of the layers are loaded in tension and the other half is loaded in compression, and the compressive strength is almost half of the tensile strength. In this case occurs nearly no degradation due to fatigue loading as only low amplitudes is applicable (Hartwig, et al., 1998).

The study made by Couillard and Schwartz (1997) show that the fatigue damage was a loss of bending moment and the loss in bending moment followed an exponential decay up to 10^6 cycles (Couillard & Schwartz, 1997) (Weber & Schwartz, 2001). Another study of the bending behaviour of composite materials was done by Tomita et al. (2001). In the study materials with two different ply orientations: [0/90][1] and quasi-isotropic with different average tensile stress for each orientation was used. For the [0/90] composite the fatigue limit was related to the compressive strength in the 0° layers and to heat generation during fatigue. The fatigue limit was for laminates that had high resistance to interlaminar fracture or with high thermal conductivity related to the compressive stress the 0° layers in the laminate. Delaminations occurred between adjacent plies of the fatigue limit of the laminate during testing for composites with poor resistance to interlaminar fracture and because of this were the fatigue limit significantly decreased. For the quasi-isotropic laminates was the fatigue limit related to the compressive strength of the 0° layers in the composite (Tomita, et al., 2001).

[1] The angles of the layers

Studies have shown that the fatigue strength is significantly reduced with the increase of shear stress. For woven glass/epoxy tubes, $[0]_{10}$, under combined static shear and cyclic compressive loadings was the reference fatigue strength reduced with 25 per cent at 2×10^6 cycles and with the applied stress of 55 per cent of the strength value (Quaresimin & Talreja, 2010).

4.2 Deeper understanding

The composite's material behaviour when applied to fatigue loading and other factors that may affect the behaviour is described in this section. The section is divided into two parts: the material and other factors.

4.2.1 Material

This chapter describes what happens to the material during fatigue loadings, and how the material's design affects the fatigue behaviour of the composite.

4.2.1.1 Fibre and matrix behaviour

As mentioned earlier starts damage due to fatigue generally because of damage accumulation (Weber & Schwartz, 2001) caused by interaction between different damage modes, such as delamination, matrix failure, fibre pull-out or fibre fracture (Vassilopoulos & Keller, 2011b). Matrix cracks are one of the most pervasive damage modes for quasi-isotropic laminates (Case & Reifsnider, 2003); the damage starts in the plies perpendicular to the loading direction. The cracks grow and propagate transverse to the loading direction across the ply thickness, due of these cracks single fibres start to break and to debond from the matrix near the broken fibre ends, Figure 14 (Case & Reifsnider, 2003) (Drechsler, et al., 2009).

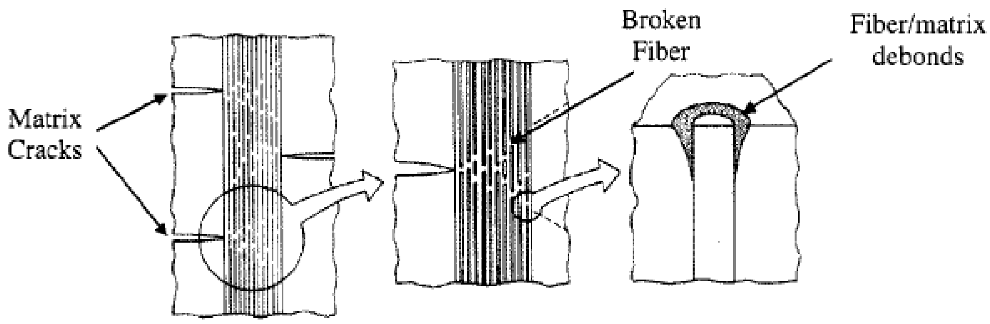

Figure 14. Matrix crack, broken fibres and fibre/matrix debonds (Case & Reifsnider, 2003, p. 416)

When a multidirectional composite is applied to cyclic loading conditions these micro-cracks play a critical role in development of succeeding damage. These fractures are critical for the in-plane behaviour and affect both the strength and the stiffness of the composite. The fractures are difficult to detect and are therefore an important damage, and the degradation of fibres are less studied than many other damage modes (Case & Reifsnider, 2003). Degradation of fibres occurs generally in composite systems with brittle matrix materials, such as graphite/epoxy and glass/epoxy systems. Moderate amounts of micro-cracks have generally small, or no effect on the strength of the lamina or laminate. These micro-cracks can however affect other properties and performances; the global stiffness can for example significantly change (Case & Reifsnider, 2003). Interfacial debonding occurs for composites consisting of a polymer matrix general close to the end of the fibre fracture and in this region transverse matrix crack may also occur. The composite will show little or no reduction in strength during cyclic loading if the fibres are not degrading under the loading and if the strains are insufficient to generate fatigue effects in the matrix. This condition is often found in carbon/epoxy composites (Couillard & Schwartz, 1997). Off-axis tensile loading is loading in all directions other than parallel or perpendicular to the fibre direction (Case & Reifsnider, 2003). The ultimate off-axis fatigue failure for unidirectional composites, consisting of high stiffness and strength fibres and a brittle polymer matrix, takes place in the single weakest cross-section, parallel to the fibre and thickness direction regardless of off-axis angle (Kawai, et al., 2001). It is important to understand the fatigue crack propagation behaviours of epoxy composites as those composites are often used in engineering components that are subjected to cyclic loading. Khan et al. (2010) mention in their study that Curtis found that if epoxy matrices have a high ductility is a higher compressive fatigue resistance exhibited (Khan, et al., 2010).

It is not possible for the matrix to easily deform in a non-linear way, and it is therefore difficult to relax any stress concentration. The matrix will instead work to reduce stress concentration and redistributing the loads in the composite, the stress and strain is then increased in the 0° plies. The matrix can usually not propagate to the next ply if the difference in fibre orientation is large enough, but most of the cracks propagate though the thickness of the ply. Parallel to the fibres and in the 0° plies will matrix cracks, i.e. splitting form, and the composite will fail when these plies fails. The splitting cracks are randomly distributed through the specimen and the distance between the splitting cracks larger than for the transverse matrix cracks. It has been observed that most of the fibre failure and damage localisation occur during the last ten per cent of a laminate’s life. An accelerating rate of damage development, characterised by the localisation of damage zones of increasing crack interaction is shown to occur during the last part of a composite’s life. The coalescence of micro-cracks and development of macro-cracks are involved in this acceleration (Nyman, 1999).

4.2.1.2 Material properties

Many factors affects how composites response to fatigue, the thicker the laminate is the less sensitive it is to impact damage and fatigue (Tai, et al., 1999), but it is not only the actual design of the component that affects how the composite responses to fatigue. The material properties such as fibre arrangement, volume fraction on both fibre and matrix, and fibre and interface properties also affect the response (Couillard & Schwartz, 1997). Other factors such as off-axis angle, degree of multiaxiality, load phase shift and stress concentration can affect the fatigue strength of continuous fibre reinforced composites. The fatigue behaviour of composites is not proportional and it can depend on the material system and the stacking sequence and possibly on the loading conditions (Quaresimin & Talreja, 2010).

Orientation, lay-up and fibre volume fraction

The orientation of each layer of the composite affects the materials’ behaviour; there are differences between how multidirectional and unidirectional composites behave and every new lay-up results in a new material that has to be tested (Nyman, 1996). The stacking sequence affects the development of damage mechanisms, if a high percentage of fibres are parallel to the loading direction less damage will accumulate during fatigue life, and less stiffness degradation will subsequently occur (Vassilopoulos & Keller, 2011a). Because of the close relationship between damage states and the anisotropy and heterogeneity different stress levels are developed. Those stress levels are dependent on the lay-up sequence and orientation of the laminate (Khan, et al., 2010). The mechanical performance of a composite material is mainly influenced by the fibre orientation. The optimum utilisation is possible when the fibres are placed in the loading direction, and small deviation can reduce the strength and stiffness. It is often necessary to use multidirectional composites (Drechsler, et al., 2009). More about different orientation and lay-ups can be found in appendix A.1.1 Fibres.

Another way to affect the mechanical performance of a composite is by fibre volume fraction, high fibre volume fraction, typically about 55 to 60 per cent, is important to achieve high mechanical performance of a composite. This to avoid fibre curvature of misalignment and to limit the void content in the resin, preferably to less than three per cent of the composites volume (Drechsler, et al., 2009).

The growth of delamination is also dependent of the lay-up of the plies in the composite (Nyman, 1999), and it is one reason for fatigue failure (Couillard & Schwartz, 1997). Delaminations can according to Nyman (1999) propagate differently depending on the number of layers: in a $[0/90_3]_S$ [2] laminate were delaminations found to propagate perpendicular to the loading direction, but in a $[0/90_2]_S$ laminate were they parallel to the loading direction. The area where delamination has occurred can at some interfaces be very large and towards the end of the composite's fatigue life are the different plies more or less isolated from each other (Nyman, 1999).

Thickness

The thickness of the laminate is affecting how sensitive it is to fatigue loading. The thicker the laminate is the better its resistance is to fatigue loading and it does not change when the composites are subjected to low-energy impact (Tai, et al., 1999).

Joints

The joints used for transferring loads from one part of the structure to another (Vassilopoulos & Nijssen, 2010). They are critical areas (Campbell, 2010b), and Vassilopoulos and Nijssen (2010) mean that they can be the weak link. Fatigue mainly affects the weak links of the composite, the structural integrity of these areas is therefore very important for the viability of the whole structure (Vassilopoulos & Nijssen, 2010). More information about joints can be found in appendix A.3.2 Joining.

4.2.2 Other factors

The material properties and the behaviour under fatigue loading are not only affected by the material, other factors can also affect the behaviour. Such factors can be: loading rate, temperature and humidity, mean stress and load frequency (Vassilopoulos & Keller, 2011a). Environmental factors and impact damages are described in this section.

[2] If the laminate are oriented according to $[0/90_3]_S$ is the 90°-direction repeated three times: $[0/90/90/90/]_s$, and the s outside the brackets means that the lay-up is symmetric: [0/90/90/90/90/90/90/0].

4.2.2.1 Environment

Temperature and moisture content are significantly affecting the strength of a polymer matrix and the adhesive strength of fibre-matrix interface (Kawai, et al., 2001) (Case & Reifsnider, 2003). This section describes those two factors.

Temperature

Temperature affects both the fibre- and matrix-dominated properties of a composite. The properties dominated by the matrix decreases usually with increasing temperature, while cold temperatures somewhat affect fibre-dominated properties. The effects in the latter case are however not as serious as when matrix dominated properties are affected by temperature (Campbell, 2010c). A study made by Kawai et al. (2001) indicates that the static strength at matrix and/or the fibre-matrix interface/interphase is significantly reduced because of increased temperature. The intrinsic tensile strength of carbon fibres does however not change when the temperature is increased from room temperature to 100°C in a polymer matrix at off-axis loading. The tensile flow stress is reduced for all off-axis angles, except 0° at 100°C (Kawai, et al., 2001).

The ultimate tensile strain and strength of uni- and multidirectional CFRP is affected by the matrix fracture strain at low temperatures. Carbon fibre composites with tough matrices are advantages for low temperature applications. Unidirectional carbon fibre composites have excellent tensile fatigue behaviour for unidirectional composites at low temperature. The fatigue behaviour is slightly worse for multidirectional composites, because of the proportion of fibres in the load direction and on the influence of cracks generated in transverse layers. When CFRP has been applied to more than 10^6 cycles it takes more than 90 per cent of their initial strength in a tensile test at low temperature. In some cases are the strength of composite material below 60 per cent of the strength of laboratory specimens, this because defects in manufacturing and stress concentrations (Ahlborn, 1988).

Composite materials should not be used at higher temperatures than the material’s glass transition temperature, T_g, where the polymer changes from a rigid glassy solid into a softer flexible material. At this point the material’s structure is the same, but the cross-links in the material are not locked in position. At higher temperatures than the T_g for a composite or adhesive, the mechanical properties of the material will be slightly reduced. The composites should therefore not be used at higher temperatures. However, moisture could reduce the T_g, and as most thermoset polymers will absorb moisture, the actual temperature shall be about 30°C below the wet or saturated T_g (Campbell, 2010c).

There are no methods in literature that address the thermomechanical loads and predict the fatigue behaviour for general thermomechanical loading patterns, as far as Vassilopoulos and Keller (2011b) know. A small numbers of modelling approaches have been published, but these models use many assumptions and because of this can their applicability not be validated for data concerning different material systems (Vassilopoulos & Keller, 2011b). The elevated temperature behaviour of composite materials affects the stress distribution within the composite and must therefore be considered when the increased temperature fatigue behaviour of composites is examined (Case & Reifsnider, 2003).

Thermal strain is produced when the temperature in a composite structure changes and deformation can then occur. Thermal expansion coefficients and swelling coefficients can be used to quantify these phenomena (U.S. Department of Defense, 2002). The same phenomenon occurs when a laminate absorbs moisture as in when heated. The fibres have a much smaller swelling coefficient than the matrix, free swelling cannot take place and internal stresses develop (U.S. Department of Defense, 2002).

Moisture

How much moisture the composite absorbs depends on the matrix material and the relative humidity, but thermosetting resins generally absorb more moisture than comparable thermoplastic resins. The temperature is also affecting the moisture adsorption, if the temperature is elevated the ratio of moisture adsorption increases. The mechanical properties dominated by the matrix are affected by how much moisture the matrix has absorbed, why the matrix swells. An example of how different composites absorb moisture can be seen in Figure 15. When a composite is exposed to freeze-thaw cycles the absorbed moisture will expand during freezing, which can crack the matrix and during thermal spikes can the moisture turn into steam. The laminate will delaminate when the internal steam pressure exceeds the flatwise tensile strength of the composite (Campbell, 2010c). The significantly dependence on temperature and moisture indicates that the fatigue strength of matrix and the interface between fibre and matrix is dependent on the hydrothermal environments. Changes in properties due to thermal and hydroscopic attacks are therefore very important to consider (Kawai, et al., 2001). If the composite is applied to moisture and in combination with temperature, cracks in the composite can occur. These cracks can work as paths for later moisture ingression and subsequent damage. It can also produce mechanical stresses that can lead to damage (Case & Reifsnider, 2003).

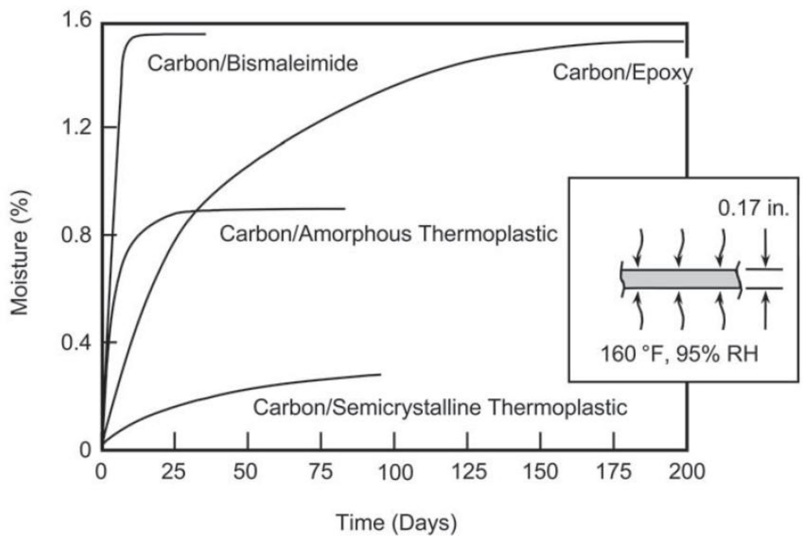

Figure 15. Adsorption of moisture for some composite materials (Campbell, 2010c, p. 19)

4.2.2.2 Impact damages

Fatigue of a composite can be affected of low-velocity impact damages, which can occur e.g. because a tool is dropped on the composite. The damages can propagate through the laminate and form a complex network of delaminations and matrix cracks, even if they may only appear as small indentations on the surface. An example of what happens to the laminate can be seen in Figure 16, where an object is dropped on the surface, and because of this matrix cracks and delamination occur. The static and fatigue strength, and the compression buckling strength can be reduced depending on the size of the delaminations. The damages can grow under fatigue loadings if they are large enough

(Campbell, 2010c). Damages produced by impact damage can be serious, especially if the composite is exposed to compression loading (Nyman, 1999) (Tai, et al., 1999). Impact damage can cause serious reduction of the structural performance, e.g. in the compressive strength and can be difficult to detect (Suemasu, 2005). The fact that they are difficult to detect is the main reason why they can be dangerous (Sebaey, et al., 2013). Low velocity impact damages are especially damaging for carbon fibre epoxy composites that are used within high performance vehicles, e.g. in aerospace, as both the fibres and the matrix are, compared to metals, elastic and brittle. The damages can be a mixture of internal lamination or back-face tension driven failure. Back-tension driven failures are initially matrix cracking or splitting between fibres, and if the bending strains are high enough the fibres fracture and further delamination will occur. These types of damage models are extremely weakening, mainly to the compression strength of the structure and when viewed from the external impacted surface they can be completely invisible. Those barely visible impact damages are a hidden threat (Davies & Zhang, 1995) and in order to be able to verify the structure different damage states have to be identified. For impact damage the structure must be able to sustain ultimate load before and after fatigue loading (Nyman, 1999). Impact damage is a function of several factors: velocity, mass, modulus and shape of the object causing the impact (Tai, et al., 1999).

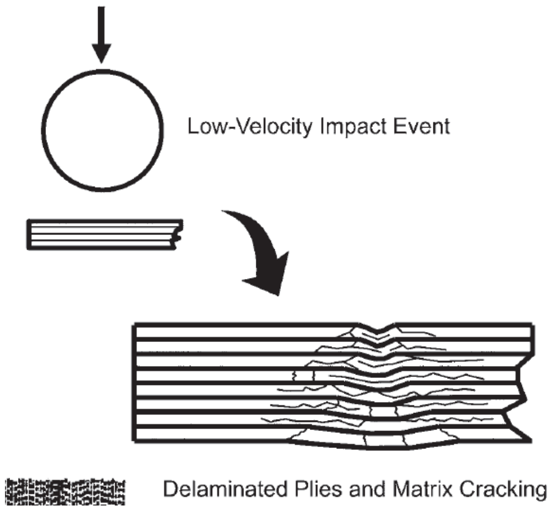

Figure 16. Low-velocity impact (Campbell, 2010c, p. 20)

Tai et al. (1999) studied the effects of thickness of a CFRP composite before and after low-energy impact and their results indicate that the thicker the laminate is the less sensitive it is to low-energy impact damages during fatigue compared to a thinner composite. Quasi-isotropic carbon/epoxy composites on tension-fatigue behaviour were tested. Impact at low energy, 20 per cent of the energy at the maximum load point was applied, and even if no or insignificant damage was produced to the laminates there was a decrease in the fatigue life. The decrease was detected to 20 per cent in fatigue life when low-velocity impact was applied for thick laminates. The tensile strength can be drastically decreased for thinner laminates because the bending effect produces an extension of the damage through the thickness. Impact damages are in thicker laminates limited to a local area because of the high bending stiffness. Thicker laminates are more reliable to fatigue loadings than thinner composites, independent of impact loadings are affecting the composite or not. The study also indicates that the fatigue response of the laminate is much more sensitive to the damage produced by impact damage that it is to tensile strength. Fatigue behaviour can therefore not be evaluated from the tensile strength (Tai, et al., 1999).

4.3 Summary fatigue

Fatigue is weakening of a material due to cyclic loadings. The fatigue behaviour for composite materials is in many ways different compared to metals, due to the inhomogeneous and anisotropic structure. In composites failure due to fatigue generally occurs because of damage accumulation caused by interaction between different damage modes, such as delamination, matrix failure, fibre pull-out or fibre fracture. Whether fatigue of composites is a problem or not is unclear, as some authors address it as the main reason for failure of composites, while others mean that composites have excellent fatigue resistance. A similar problem occurs when looking at prediction of fatigue, it seems, as there are no methods working for all composites and loadings. This because the lay-up, fibre orientation as well as the loading affect the fatigue behaviour, and in order to develop a method for all composites and loading it is necessary to gather data about fatigue properties at different material and loadings. Other factors such as temperature, moisture and impact damages affect the fatigue behaviour, which increases the complexity in predict fatigue.

Many factors affect the fatigue behaviour and composite's resistance to fatigue. The risk for failure due to fatigue increases because of any type of damage or degradation of the material properties. The following factors needs to be considered in order to reduce the risk for fatigue:

- The material:
  - The material should be selected dependent on the working environment. Polymer matrices absorb moisture and the composite's mechanical properties can decrease due to this and to varying and high temperatures. If the mechanical properties are decreased in this way the risk for fatigue increases.
- The design of the material, including fibre orientation and lay-up:
  - The more fibres in the loading directions the better is the composite to resist fatigue.
- The manufacturing:
  - Defects can decrease the material's resistance to fatigue. High quality during manufacturing is therefore important.
- The design of the component:
  - The thicker the composite is the better it is resistance to fatigue and damages.
  - Fatigue often occurs in the weak links of the material. Joints can be such link and should therefore be designed in order to minimise their impact.
  - Damages to the composite can decrease the mechanical properties. It is difficult to consider in the designing process, but by ensuring that the material can be inspected can the risk that damages affect be decreased.

5 Method and materials

This section describes the methods used to carry out the project and the material needed.

5.1 Procedure

The procedure of the project follows somewhat the structure of the report. The literature review was done first, followed by identification and a short description of the four most important problems. One of them was selected and by deeper research in the field, the consequences it may have for designing in CFRP was identified. The consequences were used as a base for the design instructions when designing in CFRP. Testing was done in order to better understand the mechanical properties of the material, and the result was used in the design instructions. Under each section the methods needed for the specific step is explained, in those cases the same methods are used at several stages references to the previous sections will be done.

Much time and focus was in the beginning of the project laid on the literature review, to describe what CFRP is, manufacturing and processing methods. Problems that can occur during manufacturing, processing and usage of carbon fibre composites in heavy-duty vehicles were identified. It has been a clear focus on finding and evaluating which problems that can occur according to literature. Based on the findings conclusions have been drawn about which problems that are the most critical: delamination, galvanic corrosion, joining and fatigue. As much earlier research has been done about delamination, galvanic corrosion and joining it was natural to focus on fatigue. Another reason to focus on fatigue was because structural components in steel are at Scania designed according to fatigue, this because it is seen as one of the most critical parameters. It was therefore assumed that fatigue was critical for composites too and should be used as a design parameter. The aim of the study was to get more knowledge about fatigue. Composites behave in many ways differently from conventional materials, and it was therefore interesting to focus on fatigue in order to get a better understanding of how it affects the designing and manufacturing of composite materials. Design guidelines were written of how to design in CFRP with focus on all four of the identified issues. Static bending and tensile tests were done with the aim to understand and to evaluate how CFRP behaves under tensile and bending loading, exposed to moisture and varying temperatures.

This was however not the initial plan for the project, in the first weeks of the project the aim was to identify, evaluate and to solve the most critical material technical problem for CFRP related to manufacturing, processing or usage. The three most critical problems should be identified, and evaluated against each other. The most critical of those problems should then be solved. The longer the project progressed and the more time that were laid on literature review and to identify the problems, the clearer it became that this would not be possible to solve within the project. It would not be enough time. It was therefore decided that one of the four critical problems should be deeper studied and guidelines for designing in CFRP should be written with a focus on all four of the most critical problems. This new focus suits well the aim of Scania, as CFRP is a very new area and more knowledge about CFRP and fatigue is needed in order to produce and manufacture structural components and vehicles in composite materials.

5.1.1 Continuously

Throughout the whole project have meetings been held, usually once a week, with a group of people with knowledge and interest in the area. The group consisted of the supervisor for the project, two other employees at the department where the project were performed and another master thesis student. The purpose of those meetings was to discuss, to help in making decisions about the project and to ensure that the project was proceeding in a preferable direction. The information gathered during the project was discussed at those meetings.

5.1.2 Literature review

The literature review was done by identifying the different aspects that are important to consider in the following parts: materials that could be used, how composites could be manufactured, how the parts could be processed and common problems that may occur. The literature review was carried out by using literature found via Chalmers library and Scania's databases, e.g. articles, research and books but also by discussing with different persons with knowledge in the area.

The purpose of the literature review was to get a better understanding of what composite materials are, how to manufacture and process them. All those stages were important for the further investigation that aimed to identify issues with implementing composite materials in the design and production of heavy-duty vehicles.

5.1.3 Problem identification and analysis

The literature review was the base for identifying problems and issues with composite materials and the four most critical problems were selected. Among those problems was fatigue chosen for further investigation, by discussions at one of the continuously meetings at Scania. It was decided to focus on fatigue because of the need of more knowledge in this specific area.

5.1.4 Further investigation

A further investigation based on the literature was done for fatigue. The investigation was divided into two major steps, general information about the problem, and deeper information. The first step was performed to get a more brief understanding of what fatigue is, based on four questions: What is it? How does it occur? Why does it occur? How can it be prevented? The deeper study focused more upon how the fibres are behaving in the composite and how the problems can be detected if it is not visible. This investigation was the basis of the work to evaluate which consequences the problem will have for the designing of components in heavy-duty vehicles.

5.1.5 Testing

In order to better understand how CFRP behaves when loadings are applied static bending and tensile tests were done. This type of tests are standard and are always done when testing material within the heavy-duty industry, it was therefore decided to do these types of tests. The purpose of the tests was to better understand how the composite material behaves under these types of loadings and different environmental exposures. The test results were used in the design instructions to better understand how the material behaves, and also for comparing to the data for the material.

5.1.6 Design guidelines

Design instructions were written in order to ease the future design work with composite materials. The guidelines were written with the study of fatigue and the other three critical issues as basis, in combination with new information from literature and own conclusions drawn from the literature.

5.2 Materials

Special equipment was needed for the tests, in order to expose the specimens to different loading conditions. The specimens were placed in two different climate chambers where different environmental cycles were progressing. The actual tests were not done at Scania, and there was therefore no need for equipment.

5.3 Testing

The aim of the tests is to better understand how the composite material behaves when exposed to moisture and temperature content, and when applied to different loading modes. Static bending tests and tensile tests were carried out within the project, because this type of loadings is common for structural components in vehicles. These tests are always done and are therefore necessary to perform before using the material. Literature indicates that moisture and temperature can affect the mechanical behaviour of composite material, see 4.2.2 Other factors, Environment. A majority of the specimens were therefore pre-treated in different environments with cycling temperatures and humidity. This was done in order to see how the environmental conditions affect the composite's mechanical properties.

The used material is a prepreg weave of carbon fibres and epoxy resin, with quasi-isotropic lay-up, cured in an autoclave by a supplier to Scania. The prepreg is manufactured by the composite company Hexcel, and is called HexPly 8552 Woven Carbon Prepregs with the fibres SPG370-8H (Hexcel Composites, 2013). The datasheet for the material can be found on the company's website, in the reference. The material was cut into specimens according to the standards used for the testing, ASTM D790-10 for bending and ASTM D3039M-08 for the tensile tests. The material combination, carbon fibres with an epoxy matrix, is the material combination that most likely will be used in a future production of structural components in heavy-duty vehicles at Scania. The prepreg was available at the supplier and was therefore selected. The specimen were cut and processed before finished, and the specimens for each test can be seen in Figure 17. It should be noticed, that the material described in the datasheet is a cross-ply weave, i.e. with plies only in the 0° and the 90°-direction, and the specimens in these tests are quasi-isotropic. The test results from the tests may be a bit lower than the given data, because the number of fibres in the loading direction is lower.

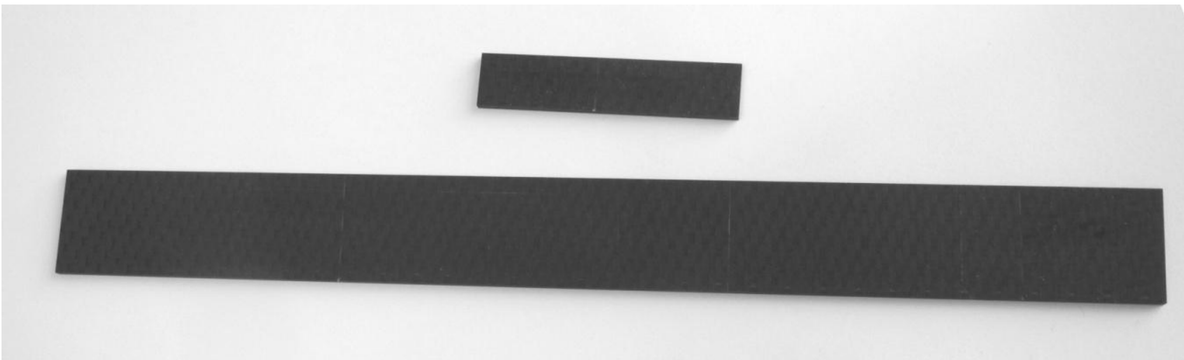

Figure 17. Specimens for bending (top) and tension (bottom)

The pre-treatment was done to see how the different environments affect the material and its strength and stiffness. At least seven tests should be carried out for the static bending test and at least five for the tensile test according to the used standards (ASTM International, 2008) (ASTM International, 2007a). In total 48 specimens were tested, 28 for static bending and 20 for tensile. They were equally divided between the three environmental cycles and the reference; in the latter case the specimens were stored at room temperature until the other environmental cycles were finished. Three cycles were carried out for three weeks with different moisture, temperature and salt content: a VDA cycle, a hydrothermal cycle and a hydrothermal cycle with salt. The VDA cycle consisted of humidity/dry cycles with five per cent sodium chloride, NaCl, cycles between 35°C and 42°C. When 42°C is applied the humidity 95 is per cent. The hydrothermal cycle was performed according to the ageing cycle described in STD4121 (Erhardsson, 2011):

1. 4 hours, 70°C and 20 % relative humidity
2. 16 hours, 38° and 95 % relative humidity
3. 4 hours, -30°C

The steps 1-2-3 were repeated 21 times, totally 21 days. The cycle was the same for both the hydrothermal and the hydrothermal with salt, but the specimens in the latter case were submerged in salt two times a week one hour at the time, see appendix C, Salt submerging in hydrothermal cycle with salt. The specimens were weighted before and after the cycles, and the data can be found in the appendix B, Weight of specimens before and after environmental exposure. The specimens were placed in a climate chamber with constant temperature of 23°C and relative humidity of 50 per cent when the cycling was finished until the test could be performed.

5.3.1 Static bending

The bending fatigue tests were performed according to the ASTM standard D790-10, Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Material. The method was used for determining the flexural properties of the material (ASTM International, 2007b). The specimens were loaded static until breakage.

Seven tests were performed for each specific condition for the static bending test, and as four conditions were tested, in 28 specimens were in total tested. There are two types of tests for bending, three or four-point bending test. The first one is used in the standard ASTM D790-07, and was also used for these tests. The composite rests on two cylindrical supports and is loaded at one point midway between the supports, Figure 18. The applied force and the resulting specimen deflection is measured until failure occurs, either at one of the outer surfaces or a maximum strain value of five per cent is reached, whichever occurs first (ASTM International, 2007b).

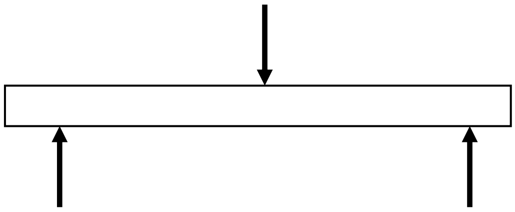

Figure 18. Principle of a three-point configuration

The specimens were dimensioned according to the standard ASTM D790. The width *(b)* should be 12.7 mm, the length between the supports *(L)* 25.4 mm for specimens thicker than 1.6 mm. The relation between the length between the supports and the thickness should be 16:1, which gives a thickness *(d)* of 1.6 mm (ASTM International, 2007b), see equations below. The length of the specimen should according to the standard be 50.8 mm, but these are 60 mm long to ensure that parts can be secured in the machine.

$$L = 16d$$

$$d = \frac{L}{16} = \frac{25.4}{16} = 1.59\ mm$$

In appendix D Calculations static bending can calculations with forces needed to be applied be found. The calculations in the appendix are based on the data from the material data for the composite, with an estimated strain of 0.01. According to those calculations should the needed force be 1.1kN, it is a little bit lower than the measured peak load that have the mean value 1.2kN. The measured strain was 0.022 mm/mm.

5.3.2 Tensile test

The tensile tests were carried out to determine the tensile in-plane properties of high performance composites according to the standard ASTM D3039/D3039M-08 (ASTM International, 2008). From the test the ultimate tensile strength, ultimate tensile strain, tensile chord modulus of elasticity, Poisson's ratio and transition strain can be obtained. The material was designed according to the standard, with a length *(L)* of 250 mm, width *(b)* of 25 mm and a thickness *(d)* of 2.5 mm (ASTM International, 2008). Twenty tests were done, five for each condition.

The specimen should according to the standard be mounted in the grips of the mechanical testing machine and monotonically loaded in tension until failure, while the force is recorded. The ultimate strength can be determined from the maximum force carried out before failure. The ultimate tensile strain, tensile modulus of elasticity, Poisson's ratio and transition strain can be derived from the stress-strain response of the material, if the coupon strain is monitored with strain or displacement transducers (ASTM International, 2008).

6 Results

This section describes the results from the tests and here is also the design guidelines presented.

6.1 Results and analysis of the tests

In order to better understand how different environments affect the composite materials they were exposed to environmental cycles as described in 5.3 Testing. The tests were done when the climate cycling was finished. This section presents how the environments and the results from the tests affected the material.

6.1.1 Moisture absorption

The specimens were weighted before and after the environment exposure. It is noticed that the weight increases or stay at the same level for all specimens, and there is small differences between the different exposures and the test types. The data indicates that the VDA exposure and the hydrothermal cycle with salt are affecting the specimens the most. It is impossible to tell whether the moisture absorption depends on the salt in the solution or the submerging itself.

A scale with four decimals and measuring in grams was used. The specimens were placed on the scale and glass doors could be closed to ensure that any draught could not affect the measuring. The specimens for the tensile tests were not possible to put direct on the scale due to their size and therefore had to be placed in a measuring cup in order to fit on the scale. It was a bit difficult to get an exact weight on the specimens, the scale show four decimals and the last two had a tendency to decrease when the specimen was placed on the scale. Often the scale was stabilised after a while, but for some specimens it was not. When removing them and placing them again the scale often showed a slightly different result, but usually with just the last two decimals different. The scale is therefore one factor that may affect the results from the testing, and the data have large uncertainties. It is however possible to draw the conclusion that the material in some way was affected by the cycling.

Lars Wistfors at Exova, who works with composite materials say that composite materials commonly needs ten to twelve weeks in humidity cycles to be fully saturated, as those specimens have only been cycled for three weeks they are not saturated. They have however absorbed some water; the data can be found in appendix B, Weight of specimens before and after environmental exposure. In Figure 19, a graph with the comparison of the absorption between the specimens can be seen. The y-axis shows the increase in weight in grams, and each figure: triangle, diamond or square symbolises a specimen. The orders the specimens are placed in have no significant meaning. In Figure 20 the rounded data is available.

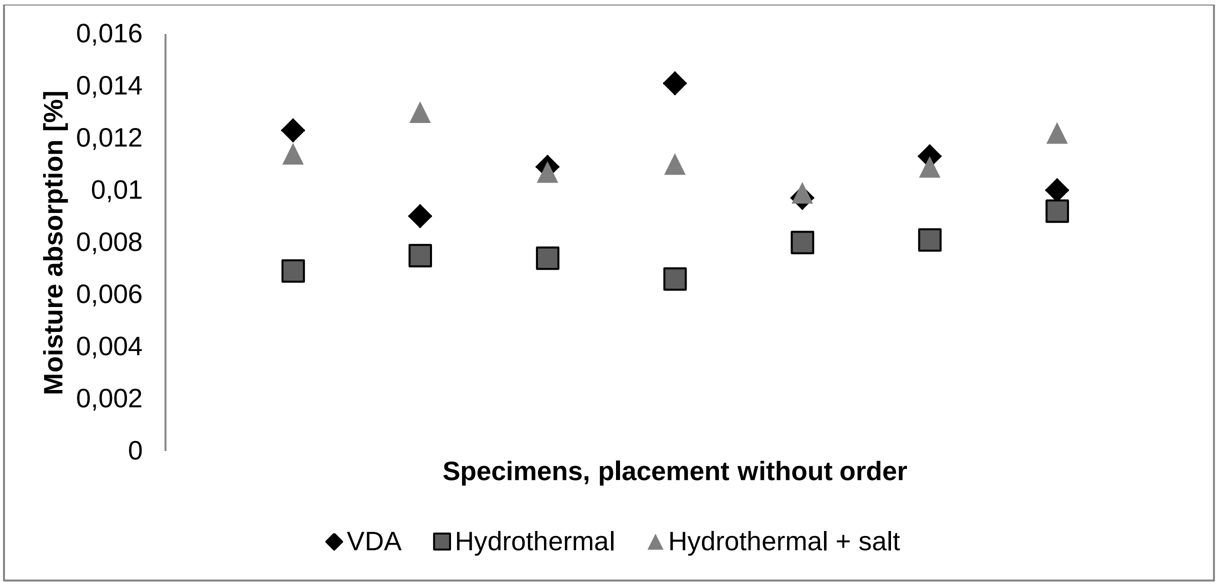

Figure 19. Moisture absorption

	Static bending	Tensile	Total average
VDA	*average*	*average*	
Weight before	2.60	21.36	
Weight after	2.61	21.44	
Increase in gram	0.01	0.08	
Increase in per cent	*0.38%*	*0.37%*	*0.38%*
Hydrothermal	*average*	*average*	
Weight before	2.56	21.07	
Weight after	2.56	21.12	
Increase in gram	0.01	0.05	
Increase in per cent	*0.22%*	*0.24%*	*0.23%*
Hydrothermal + salt	*average*	*average*	
Weight before	2.59	21.32	
Weight after	2.60	21.39	
Increase in gram	0.01	0.07	
Increase in per cent	*0.44%*	*0.31%*	*0.39%*

Figure 20. Weight of the specimens, before and after exposure, rounded off to two decimals

6.1.2 Corrosion

Corrosion could be seen on the specimens for bending tests exposed to the hydrothermal cycle with salt, Figure 21. The two types of specimens, for bending and tensile, were placed on two different grids in the climate chamber because of their different sizes. Corrosion was seen on six out of seven of the specimens used for bending and exposed to the hydrothermal and salt cycle. This phenomenon did not occur on any of the other specimens, independently of size or environmental exposure. The most likely reason is because the salt solution accelerates the corrosion process and different materials are used for the grids, which corrode differently. The grid where corrosion occurred, Figure 22, have small points of corrosion on other places than where the specimens were placed, Figure 23. The grid is probably not designed to withstand the environment in the climate chamber, and galvanic corrosion have occurred when the salt submerged specimens were placed upon it expedite the corrosion process. When scratching on the corroded surface on the grid with a fingernail, it is easily removed as can be seen on the left bar in Figure 22. These small dots of corrosion, and the fact that the corrosion caused by the specimens is easy to remove are typical behaviour of stainless steel, according to Bengt Johansson at Scania, which probably is the material in the grid.

Figure 21. Corrosion on specimen exposed to hydrothermal cycle and salt

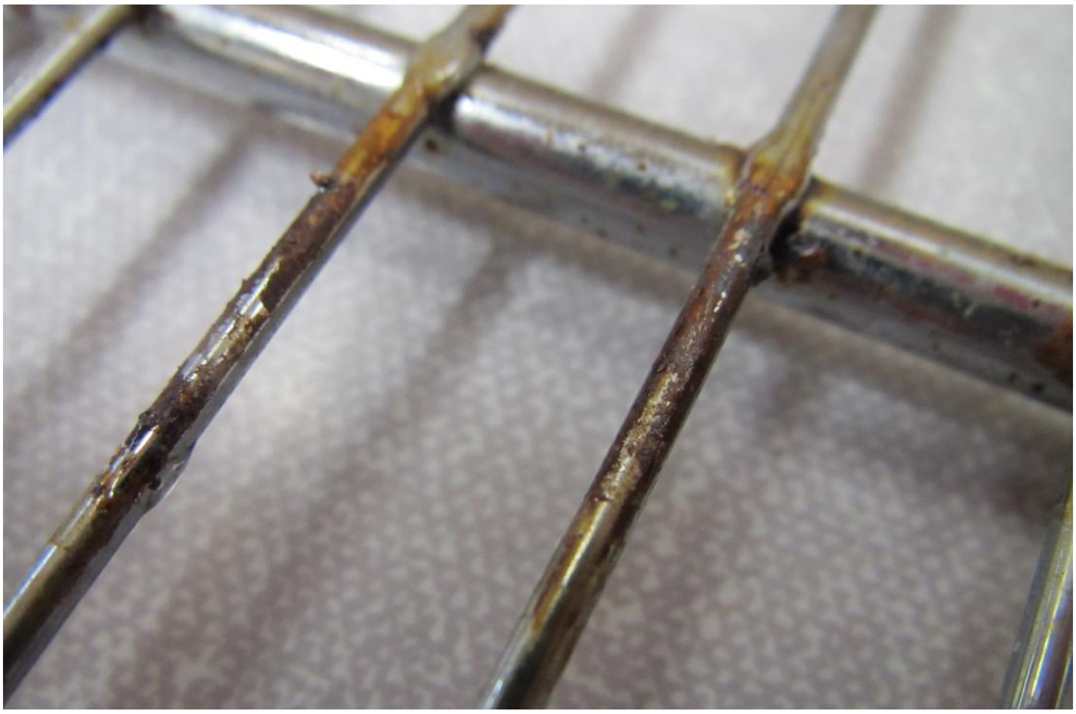

Figure 22. Corrosion where the specimens exposed to hydrothermal cycle and salt were placed

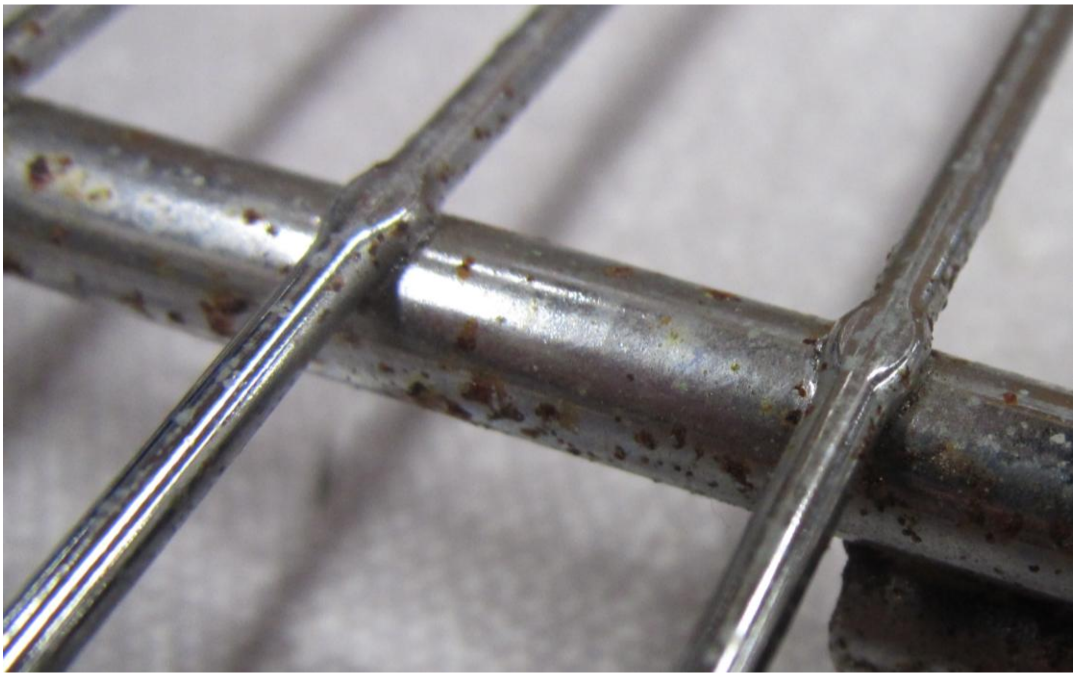

Figure 23. Points of corrosion, where the specimens were not placed

6.1.3 Static bending test

The static bending tests were performed without any difficulties. The collected data are presented below in the shape of chart diagram that shows the measured parameters. The line on top of each stack symbolises the error margin, calculated from the average value and the standard deviation. Within this area, 95 per cent of the results with the same type of specimen and the same type of test will be placed. The analysis of these tests have been based on that if the error margin for the cycled specimens are overlapping the error margin for the reference specimens, no conclusions about whether the cycles have affected the material properties or not can be drawn. The collected data can be found in appendix E.1 Static bending.

The charts below presents the data gathered from the bending tests. The peak load, Figure 24, varies between the cycles; the reference is however overlapping all of the other specimens' error margins. The cycling seems, in this case, not to have affected which load the specimens can be applied to before they break. The flexural strength, Figure 25 gives a similar result; the specimens are all within the range of the error margin of the references. In comparison to the peak load, the specimens seem to not have been affected by the different cycles. The result is however different for the flexural modulus, Figure 26, both the specimens cycled in the VDA and the hydrothermal cycle with salt have a decreased modulus in comparison to the reference, and the error margins are not overlapping. This can be an indication of how the material properties would be affected if cycled during a longer time, but the decrease is however very small and relatively few specimens were tested for each cycle. More tests needs to be done, especially with cycling for a longer time, to better understand how the mechanical properties are affected and if the VDA and the hydrothermal cycle with salt are affected more easily. It should however be noted, that these two cycles caused the highest increase in moisture absorption during the three weeks they were cycled. The result for the strain at peak, Figure 27, shows no difference at all between the reference and the different cycles.

Some of the specimens had causes corrosion on the grid, as described above. As this only occurred for the specimens applied to the hydrothermal cycle with salt, it is impossible to tell whether the corrosion had any effect on the result. The decrease in the modulus is probably rather a result of the submerging in salt solution itself than the corrosion. CFRP cannot corrode, it is the metal that corrodes, and the corrosion therefore ought to only lie on the surface.

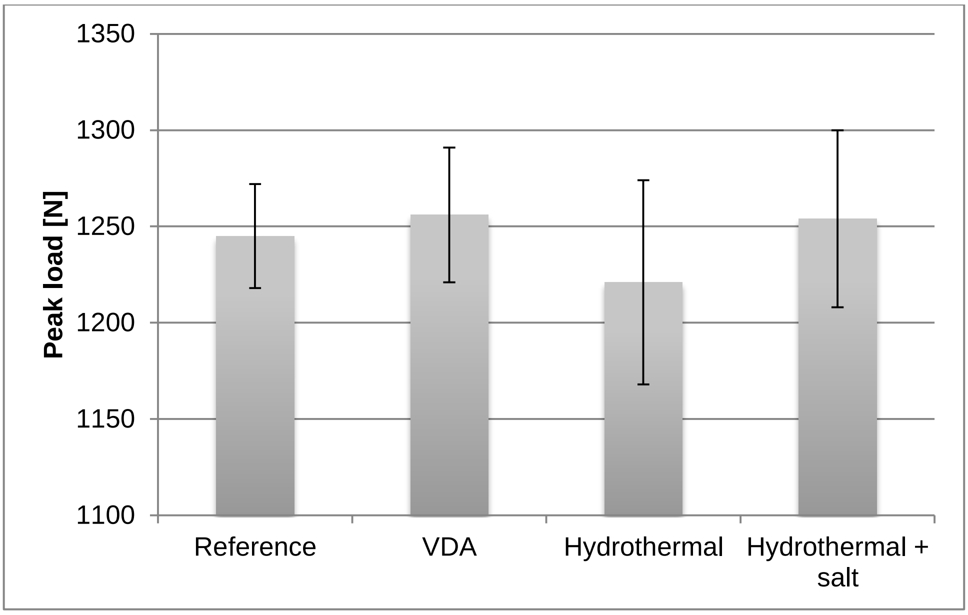

Figure 24. Peak load

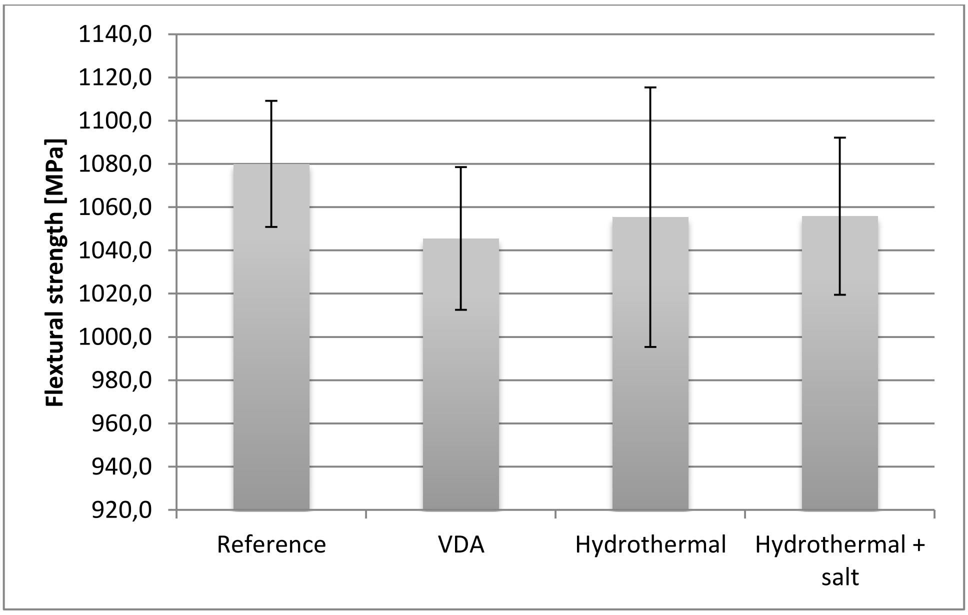

Figure 25. Flexural strength

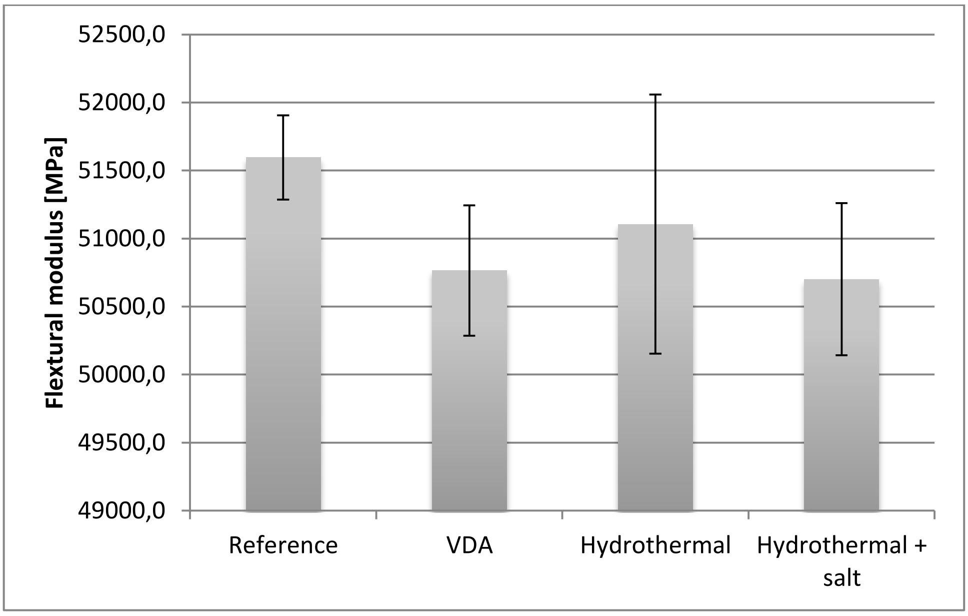

Figure 26. Flexural modulus

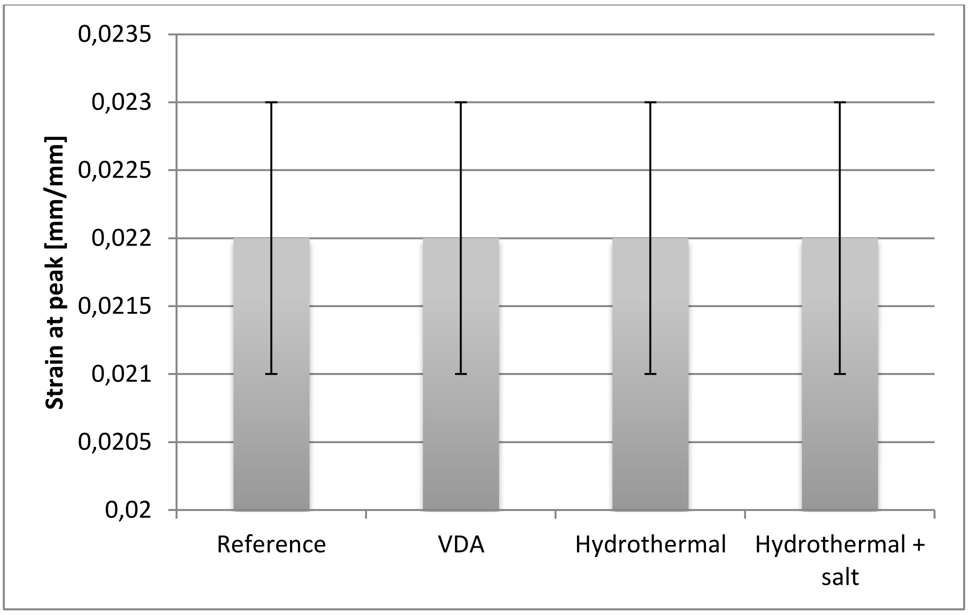

Figure 27. Strain at peak

6.1.4 Tensile test

The tensile tests were performed until failure, and Figure 28 and Figure 29 show what one specimen looked like after the test. The layers have delaminated from each other and as can be seen the fibres in the loading direction have failed, but the specimen is still hold together by fibres in the other directions. Those fibres can however not take any loads in the tensile direction and the composite has therefore failed.

Figure 28. Specimen after tensile test, from above

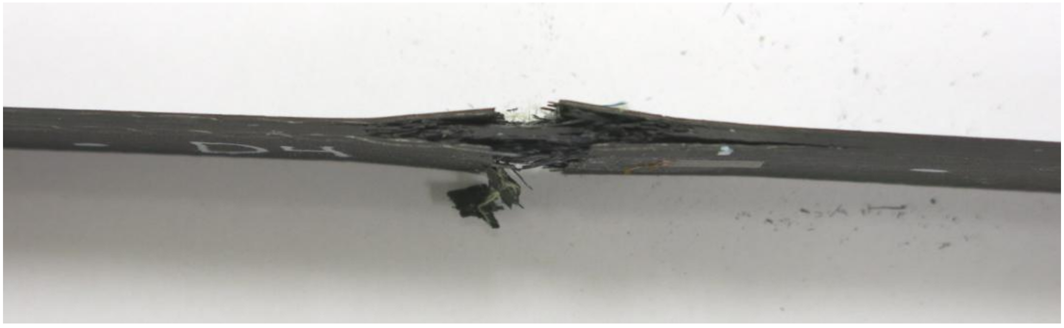

Figure 29. Specimen after tensile test, side view

The results of the tensile tests have been analysed in the same way as for the static bending tests, if the error margin for the references is overlapping the other error margins, no conclusions can be drawn about how the environmental cycles affect the mechanical properties. This occurs for the ultimate stress, Figure 30, where the error margin for the three cycles overlaps the reference. No affection of the cycles can be seen. The modulus, Figure 31, shows a reduction for the specimens that were placed in the hydrothermal cycle with salt; the other specimens are not affected. The decrease in modulus can, as mentioned for the bending tests, be an indication of what would happen if they were cycled for a longer time period. Few tests are done and more are need to get a more reliable result. The measured ultimate strain, Figure 32, varies for the specimens, but they seem to not have been affected by the cycles as the reference is overlapping all of the others. The data from the tests can be found in appendix E.2 Tensile.

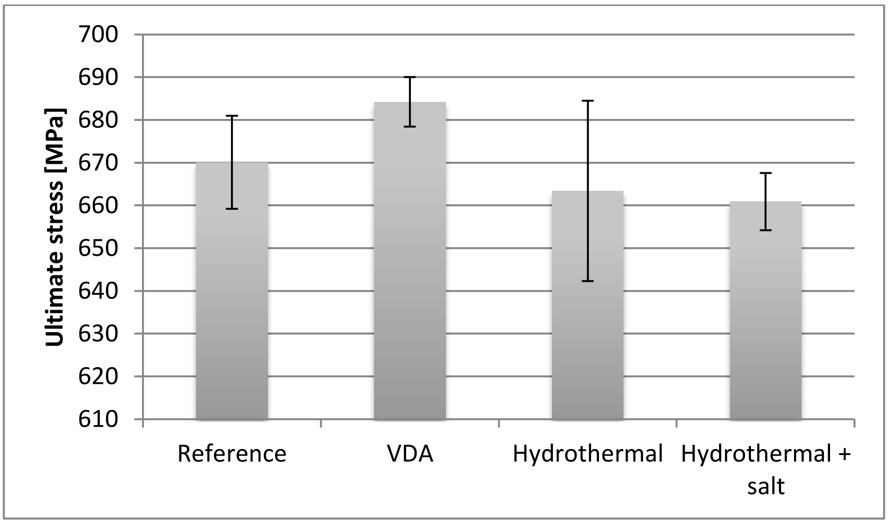

Figure 30. Ultimate stress

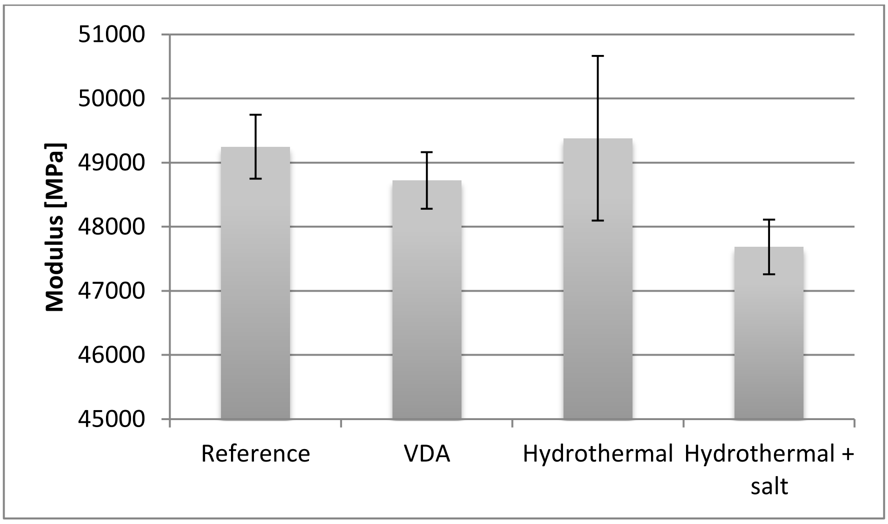

Figure 31. Modulus

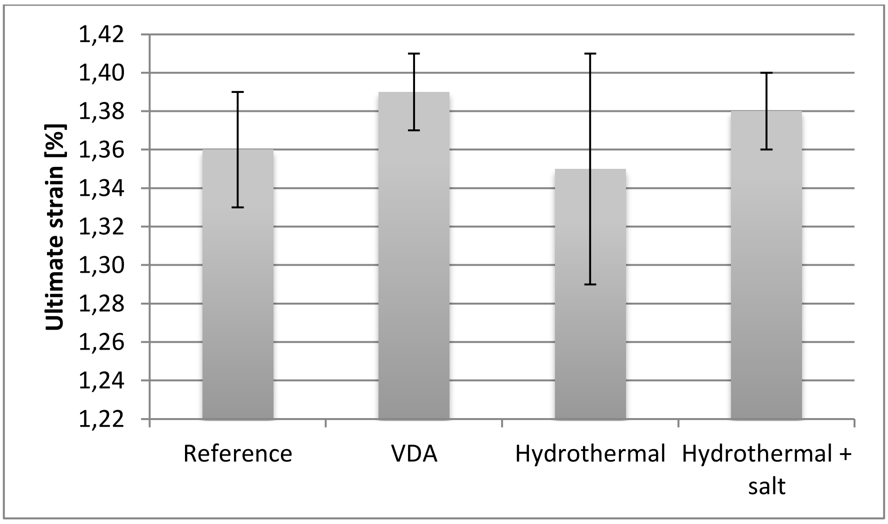

Figure 32. Ultimate strain

6.2 Designing in composite structures

This chapter describes the designing process of composite structures in CFRP and states design guidelines of how to design in the material. The chapter is divided into five major stages; each stage includes a description of the area, followed by guidelines for designing. The purpose of the description is to give general information about the steps and what the different steps includes, the guidelines are on the other hand more straightforward instructions of how to design and what is needed to considered. Much of the information in this chapter is based on the knowledge gathered during the previous chapters and the literature review, and conclusions drawn from those.

6.2.1 The design procedure

Many choices have to be made when designing in composite materials, which both increases the design freedom as well as makes the process more complex. The matrix and fibres, the lay-up and fibre orientation need to be determined, and a proper manufacturing method need to be selected (Campbell, 2010b). Fatigue and related phenomena are the most common causes of structural failures in composite materials and those are therefore necessary to consider (Vassilopoulos & Keller, 2011b). Campbell (2010c) on the other hand means that as long as reasonable strains are used fatigue should not be a problem. High coefficients of safety are generally used, because of the difficulty to accurately model the material behaviour, which in turn leads to over dimensioning of the structures. Compared to designing a structure based on static strength and stiffness, it is much more complex to design composites based on fatigue. The reason is that the material's properties change during loading. The property variation is not linear; its rate depends on how far the material is from failure, i.e. the loading conditions and material status (Vassilopoulos & Keller, 2011a).

The more I have read about designing with composite material, the more convinced I have become that fatigue may be a problem, but it is highly dependent on the type of load and other design parameters are more critical. Fatigue is rarely mentioned when reading about designing in composite materials; instead factors such as the fibre orientation, type of material, loading etc. are more common. The conclusion that has been drawn from that is that fatigue is important to have in mind when designing, but other factors are more critical and are therefore necessary to prioritise. The main focus in the design sections will therefore not lie specifically on fatigue, but on all those issues identified as critical, and how those may affect the design in composite materials.

The design process for structures in CFRP has been divided into four major steps: the material selection, manufacturing method, material design and structural design, and these four steps are necessary to carry out in order to design and develop composite parts. According to Campbell (2010b) it is common that the steps in the design process are iteratively, especially in the early stages of the design process. When the design is set, it is expensive to go back and change it, and most of the costs are set in the first stages of the process. Preparation before the final design starts is therefore important (Campbell, 2010b). It is almost impossible to finalise one step before starting the next. Which manufacturing process to use is affected by the selected material, and the complexity of the design, on the same time as the manufacturing process affects those other steps. The information gathered in the different steps needs therefore to be used in the other steps during the whole designing phase. It is however possible that one parameter is set from the beginning, e.g. a manufacturing method is used within the company and is a proper method to continue to use. Then the manufacturing process must be used as an input to the designing process itself. Figure 33 shows one way to illustrate the process.

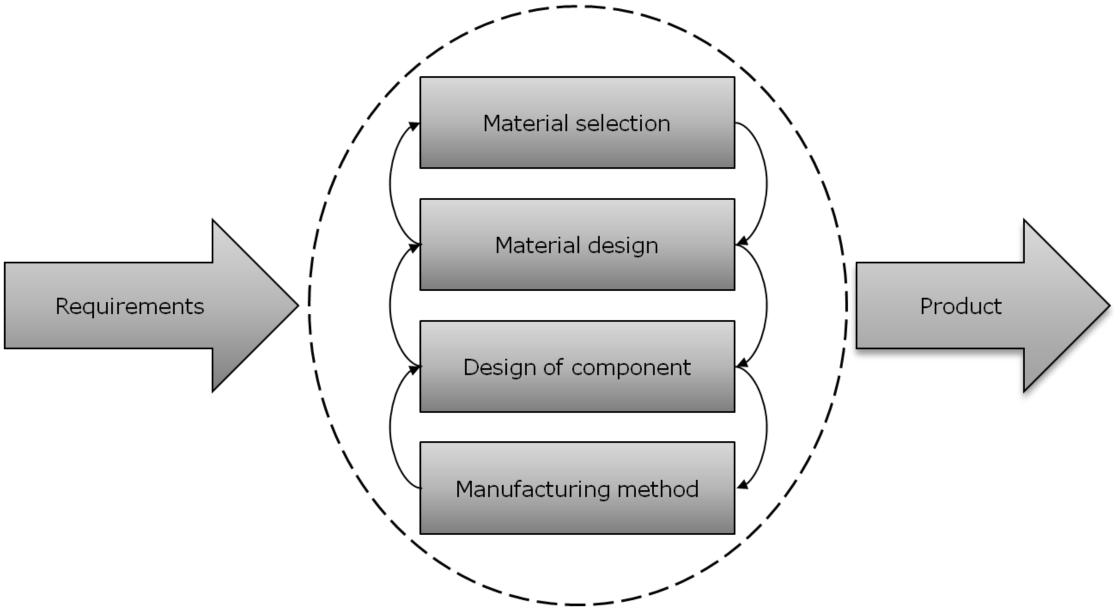

Figure 33. The design process

The requirements on the product have to be set before starting the design procedure and in order to know the parameters that affect the designing process. The following factors are necessary to determine:

1. The type of loading, e.g. axial, bending, torsion or a combination
2. Mode of loading, e.g. static, fatigue, impact, etc.
3. Service life
4. Operating or service environment, e.g. temperature, humidity, presence of chemicals etc.
5. Other structures or components which the considered design is required to interact with
6. Manufacturing processes that can be used to produce the structure or component
7. Cost, both material cost and the costs to transform the selected material into a final product, e.g. manufacturing, machining and assembly costs (Mallick, 2007b)

It is necessary to calculate which stresses and strains that will be applied to the composite, and what it should be designed to withstand. It can be done by using design allowables and safety factors to get the ultimate design limit; it is the limit the composite should be designed according to. Design allowables are the limit of stress, strain or stiffness that is allowed for a specific material, configuration, application and environmental condition. The values are statistically determined from test data generated during the building block approach. The design allowables must account for all varying material properties that reasonably can be expected in the manufacturing and assembly of a composite part. Manufacturing process variations and acceptable anomalies and limitations of structural analysis must also be taken into account. It is necessary to select appropriate design allowables for composite structures to ensure safe and efficient use of the materials (Campbell, 2010b).

The strength a structure must be able to withstand is based on the ultimate combination of loads that will be applied under the most severe environmental conditions for the structure. To ensure that the structure will not fail at this condition a safety factor is applied (Campbell, 2010b). Safety factors are defined to reduce uncertainties on (Gay, et al., 2002):

- The magnitude of mechanical characteristics of reinforcement and matrix
- The stress concentrations
- The imperfection of the hypothesis for calculation
- The fabrication process
- The aging of material

The safety factor is multiplied with the design limit load gathered from the design allowables, to get the design ultimate load. A structure that have the design limit load 1,000 kg, should be designed to withstand 1,500 kg, if the safety factor is 1.5 (1,000 × 1.5 = 1,500).

$$Design\, ultimate\, load = design\, limit\, load\ \times safety\, factor$$

The safety factor for aerospace structures is 1.5, and for structures where weight is not an issue safety factors between six and ten are used. Industry regulations are often mandating the safety factors (Campbell, 2010b). Mallick (2007a) on the other hand say that safety factors for fibre composites often are two or more, mainly to owe the lack of design and field experiments with composite materials. This is well suiting the safety factors that CCG, Composite consulting group, uses for wind turbines and derricks. They use safety factors recommended by Det Norske Veritas and Lloyd which are between 2.5 and 3.5 for composites (Jönsson, 2013). Safety factors for composite materials depending to the loading type are according to Gay et al. (2002) [3]:

High volume composites:		
Static loading:	Short duration:	2
	Long duration:	4
Intermittent loading over long term:		4
Cyclic loading:		5
Impact loading:		10
High performance composites:		1.3 to 1.8

Another method for designing extra strength into a composite structure is by using a margin of safety. When the safety factor has been applied to the design load and the laminate is designed to withstand the loading condition any extra load-carrying capability is seen as a margin of safety (Campbell, 2010b).

In the early phases of the design process, trade studies are often done in order to determine the best material, manufacturing process and structural configuration for a given part. Several designs and materials are often compared in this step. It is in the trade studies the design team determines the requirements on the profile, such as stiffness, weight, fatigue resistance, nonrecurring and recurring costs, and damage tolerance/reparability. When the requirements are decided they are assigned relative to weight factors to identify their importance. The different concept can then be evaluated (Campbell, 2010b) and the most proper choice selected. The data from the trade studies can be used

[3] Safety factors for steel are often 1.5 or 1.95 if the material is critical to fatigue.

to evaluate different concepts against each other in order to choose the option with the best properties for the specific case.

Knowledge is one factor that is important when designing in composite material; it is necessary to understand how the material behaves and how different factors affect the mechanical properties. Based on this project and discussions with people at Scania, there is a lack of knowledge of how to design in carbon fibre composites within the heavy duty vehicle industry, especially because few of the designers have used carbon fibre composites for designing. To be able to implement composite materials in the design process it is therefore necessary to educate and to have proper tools for validating the structure. Mangino et al. (2007) have however another point of view and mean that automotive designers have an understanding of designing in composite materials, but there is an absence of adequate simulation software for all design phases. Weber (2010) has interviewed different persons within the industry, and many of them believe that there is a lack of knowledge regarding composites and people need to learn more about what composite materials are and how they behave, as the personal definition of what composites are differs (Weber, 2010).

6.2.1.1 Design concepts and parameters

There are at least two alternative design concepts for predicting the fatigue life for structural components in composite material: *damage tolerant* (or fail-safe) and *safe-life* design concepts. For damage tolerant concepts it is assumed that a damage metric, e.g. crack length, delamination area, or residual strength or stiffness, can be correlated to fatigue life via a valid criterion. The damage is allowed as long as it is not critical and cannot lead to sudden failure. Structures based on safe-life design are allowed to operate as long as no measureable cracks are initiated. Cyclic stress or strain in safe-life designs is directly associated with operational life via the S-N or ε-N curves. Wind turbine rotor blades are examples of safe-life designed structures. Rotor blades are used and are cost effective for 20 to 30 years. The rotor blades have been exposed to 10^8 to 10^9 loading cycles with variable amplitude when they are removed from the turbine. Those rotor blades are however commonly designed in glass fibre reinforced plastics. The load spectrum is defined by different stochastic and deterministic cases defined by the loading fluctuations (Vassilopoulos, 2010).

When designing in fibre-reinforced composite materials it is common to use the same design criteria as for metals. The following criteria are used for designing primary structural components in an aeroplane, whether if it is made from aluminium or CFRP (Mallick, 2007a):

1. The structure must sustain the ultimate design load in static testing.
2. The fatigue life must be equal to or exceed the projected vehicle life.
3. Deformations that result from the applied cyclic loadings and limit design shall not interfere with the mechanical operation of the aeroplane, adversely affect its aerodynamic characteristics, or require repair or replacement of parts.

Other important parameters when designing in composite materials are crashworthiness and durability, and the crashworthiness is especially important when designing for the automotive industry. If composites are properly designed the material can offer excellent crash performance, where the specific energy absorptions are better than for metals. The material's crash performance is expensive to test, especially in full-scale, as it requires very specialised equipment and the structure cannot be reused after testing. There are data programs for these kinds of simulations, but there is a lack of reliable data properties for composite materials. It can take very long time to simulate crashworthiness, and this is rather the problem than lack of material with the right properties (Mangino, et al., 2007). Another important factor when designing in composite materials is the durability of the material. The durability impact of cyclic loads is likely to be disregarded if durability is evaluated on the basic of static strength calculations. If fatigue life prediction methodologies were introduced into durability simulations durability performance could be assessed early in the product development process and establish recommendations for guiding major design choices (Vassilopoulos & Keller, 2011b).

6.2.1.2 Verification of composite structures

There are several ways to verify that a composite structure can resist the applied loads and parameters that may affect it. Design allowables and safety factors are both used to ensure that the composite would not fail. High coefficients of safety are generally used when designing composite structures, due to the inability to accurately model the material behaviour. With exception of methods that already are used, composite structures are over dimensioned because of the stochastic nature of fatigue loadings. It is necessary to characterise each material and to appropriate model the quasi-isotropic and fatigue behaviour to develop theories that assist the design process (Vassilopoulos & Keller, 2011a).

The building block approach can be used to ensure that the component and assembly can withstand the applied loads and forces, Figure 34. The method is based on a number of levels including various numbers of tests to more or less complicated structures. In the first levels a large number of simple specimen are tested, and the tests become fewer and the structures more complicated for each level. The top level often includes testing of the final design. The basic material properties are determined on the lower levels by using large numbers of specimens from several batches of material. The gathered data from the lower levels are then used to predict failure modes and loads on higher levels. The approach gives the opportunity to develop and refine the tooling and processing approaches that later can be used in the production. The test method is expensive, as a large number of tests need to be done, however it has been successful for design and build e.g. aeroplane systems, where safety is extremely important (Campbell, 2010b).

Scale up is one way of testing the material’s resistance to loads; a specimen is tested and scaled up to the structural part. One issue with this is that the test results of strength and fatigue will not necessary be the same for the structural part as for the specimen (Nyman, 1996).

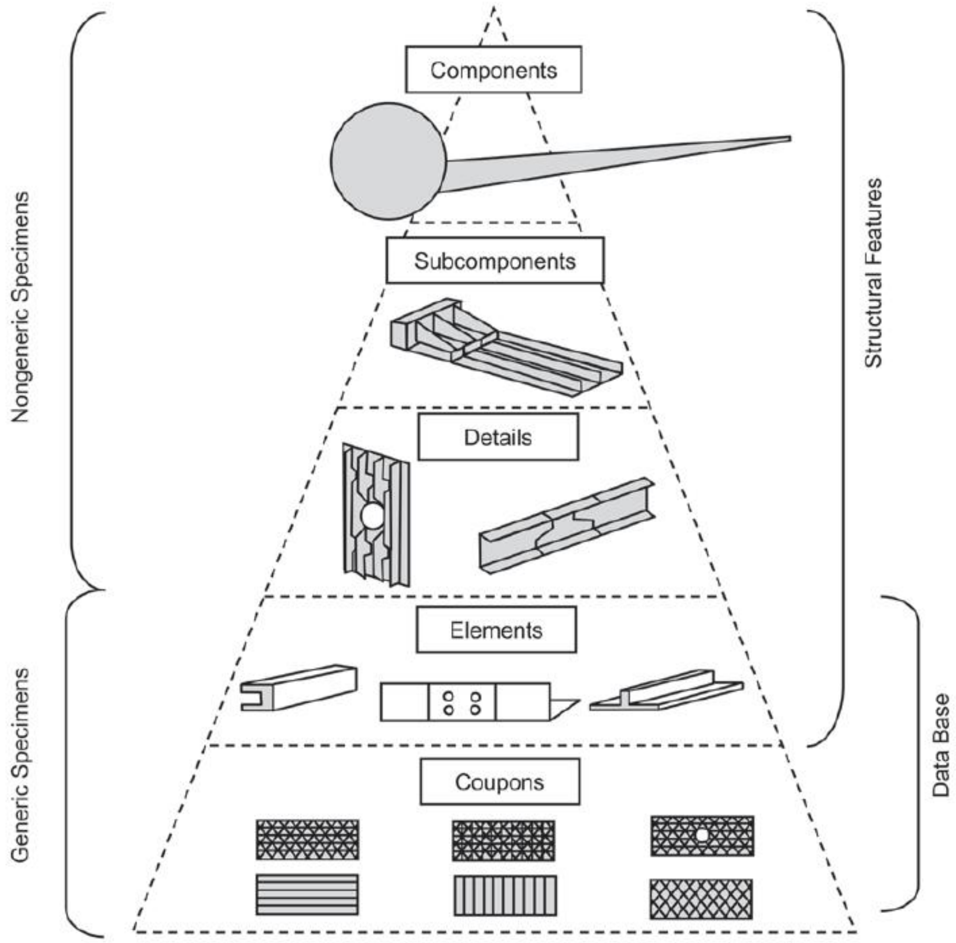

Figure 34. The building block approach (Campbell, 2010b, p. 500)

6.2.1.3 Guidelines

The first thing to do before designing the component is to calculate the stresses and strains that are applied to the composite by topology and how the component should look like if there was no limitations in the design. Requirements for the composite needs to be specified, the stresses and strain will be determined from the topology examination, but other requirements needs to be set, such as, the type and mode of loading, how long the structure should last, in which environment it should be working in and other structures it should interact with and the interface between the components. The manufacturing process can be set here, but it can also be decided during the designing process, iteratively with the other stages. In this step is also the costs for the project determined, both the material costs and manufacturing, machining and assembly costs.

Design allowables and safety factors, as described earlier in this chapter are important parameters when designing in order to set what the structure should be designed to withstand to ensure that it will not fail. The design allowables is the design limit load, the maximum load that will be applied to the composite. The allowables are multiplied with a safety factor to get the ultimate design load, the load the composite should be designed to withstand. How high the safety factor should be varies, dependent on the type of load and composite. The safety factors recommended by to Gay et al. (2002) vary a lot between high volume composites and high performance composites. Within the aerospace industry is a safety factor of 1.5 used (Campbell, 2010b), but for other structures where weight is not an issue should the safety factors be between six and ten. Mallick (2007a) means that the safety factor for fibre composites often is two or higher. One reason for the very different opinions of how high the safety factors should be could depend on the type of the material. High performance composite is the material that is the most interesting for the heavy-duty industry, and then be somewhere around two or maybe a bit higher, but not as high as six to ten as Campbell (2010b) recommends.

It is also important to have in mind that the material selection and design, design of the structure and the selection of manufacturing method are done iteratively, at least in the early phases of the designing. The manufacturing method is depending on the volume and quality as well as on the used material. The design of the structure may need to be done in different ways depending on the selection of materials as the fibres and matrix have different properties.

There are some general parameters to follow when designing in composite materials, and which are important to have in mind during all stages in the designing process:

- Design in a way that allows inspection of the structure, both under production and when in service (U.S. Department of Defense, 2002) (Campbell, 2010b).
- If it is possible stress risers should be eliminated and reduced, as they can reduce the static strength of the composite (U.S. Department of Defense, 2002) (Campbell, 2010b).
    - The structure should not be optimised for the most severe case if multiple loads can occur; there is a risk that that large resin stresses for the other cases is produced.

Composite structures behave differently depending on the design and the loading. Structures should therefore be designed differently depending on if it is applied to tension or compression. The following parameters are important when designing in composite materials:

- Tension (Campbell, 2010c)
    - Dry structures in cold temperatures have the worst behaviour in tension loadings and should therefore be used when designing.
    - Avoid filled holes when tension is the most critical, especially if the laminate has a majority of the plies oriented in the loading direction.
- Compression (Campbell, 2010c)
    - Structures sensitive for compression should be designed according to the material behaviour for hot-wet environments.
    - Avoid open holes when compression is the most critical.
- Fatigue
    - Under fatigue cycling in unidirectional composites is strain the appropriate parameter instead of stress, as long as no modulus degradation occurs during the cycling (Hartwig, et al., 1998).
    - Fatigue should not be a problem as long as reasonable strains are used during designing (Campbell, 2010c).

6.2.2 Manufacturing

The manufacturing process is either decided in the requirements and works as an input to the designing process, or is selected in parallel with the other stages. The selected materials are often an important factor of which process to choose, as all materials are not suitable for all processes

(Campbell, 2010b). The manufacturing method affects the composite's mechanical performance and properties. It is therefore important to select a manufacturing method that can ensure the quality of the component. Wrinkles and voids are damages commonly caused by the manufacturing process, and can act as sites for failure due to fatigue. The composite risk to fail because of this, as described in 4.1.2 How fatigue occurs. The selection of a proper manufacturing method to use is also dependent on the material that will be used, as some processes are not suitable for all types of composite material, e.g. compression moulding is mainly used for thermoplastic resins and not thermoset. The manufacturing volume and complexity of the structures are other factors to consider. More information about the manufacturing processes can be found in appendix A.2 Manufacturing methods**.**

The lack of suitable manufacturing processes is one of the main reasons why composite materials are not widely used for mass production. Composite materials are neither particular used within the heavy-duty vehicles industry. The automotive industry often requires manufacturing of high volume components, and according to Mangino et al. (2007) the truck industry can have volumes between 5,000 and 20,000 parts per year, while for cars it might be 80,000 to 500,000 parts per year, or even more. In comparison Scania produced more than 60,000 trucks and 6,000 buses in 2012 (Scania AB, 2013). Mangino et al. (2007) mention RTM as one possible manufacturing method, for medium volume composite production. The manufacturers of composite material are working to become more competitive for automotive industry (Mangino, et al., 2007).

6.2.3 Material selection and material design

This section considers both the material selection and the material design process. Both stages are included because of their dependency on each other.

6.2.3.1 Material selection

The material selection is one of the most critical steps of the designing process. If it is not done properly there is a risk for poor material performance, requirement of frequent maintenance, repair or replacement. In extreme cases it can cause damages, injuries or fatalities. In order to select a proper material it is necessary to have good knowledge of the performance requirements of the considered component or structure, which is set in the phases before the design process starts.

There are many factors affecting the material properties, as described in 4.2 Deeper understanding, and have to be considered when selecting fibres and matrix. It is however not only to select a proper matrix and fibres, the materials come in many variations with different advantages and disadvantages. The fibres can be continuous or discontinuous (short); oriented or disoriented, and can be furnished as dry fibres or pre-impregnated with matrix. The more operations the supplier needs to do, the more expensive the product form in general is, for example prepreg is more expensive than dry woven cloth. In this study the focus lies on continuous fibres, that can come in many different variations: collected in rovings, tows or yarns, which are the most common, and they can in turn be chopped, woven, stitched, or prepreged into other product forms. Depending on the manufacturing method, different fibre forms should be used; in pultrusion and filament winding rovings is for example the most common used product form. Prepreg is fibres pre-impregnated with matrix, and many different variations are available. Many fibre and matrix combinations are available, all combinations are however not available for all material forms (Campbell, 2010b). For more information about the material types and manufacturing methods see appendix A.1 Composites and A.2 Manufacturing methods**.**

It is the fibres that provide the strength and stiffness of the composite; it is therefore appropriate to select the fibre first. The matrix protects the fibres and keeps them in their position, and provides the matrix-dependent properties. If the matrix is properly chosen it provides resistance to heat, chemicals and moisture. The following factors should be considered and the material chosen dependent on the primary design parameters, when selecting between glass, aramid and carbon fibres (Campbell, 2010b):

- Tensile strength
- Tensile modulus
- Tensile strain (Jönsson, 2013)
- Compression strength
- Compression modulus
- Compressive strain (Jönsson, 2013)
- Coefficient of thermal expansion
- Impact strength
- Environmental resistance
- Cost

Carbon fibres are advantageous over both glass and aramid fibres if tensile modulus and compression modulus are the most important parameters. Carbon fibres are brittle and if impact strength is important the material should be avoided, but the resin has however influence over the impact strength. If carbon fibres are used at higher temperatures than 370°C the material starts to oxidise (Campbell, 2010b). The first thing to consider when selecting matrix is the service temperature required. The matrix should be selected so that the glass transition temperature is 30 to 40°C above the service temperature. The glass transition temperature is a good indicator of the matrix temperature capability. The polymer should not be used above this temperature, as above the limit the material starts to degrade and reshape. It is important to have a thorough understanding of the environment the matrix will be used in when selecting matrix as their resistance to moisture and temperature are different (Campbell, 2010b). The matrix is more sensitive to environmental impact than the fibres, and there is a risk that it corrodes away if exposed to heat, small impacts or to ultraviolet rays, resulting in unprotected fibres. This risk can however be minimised by using a good surface finish, control the service temperature, and by keeping the edges and fastener holes trimmed (Campbell, 2010b).

Trucks and mass transit vehicles are used in an environment that can be both humid and with diverse temperatures, due to varying weather conditions and it is therefore necessary to select matrix and fibres to minimise the risk for reduced strength and stiffness due to this. Temperature and moisture can significantly reduce the mechanical strength of a composite, especially when they are combined and must therefore be taken into consideration for heavy-duty vehicles. A more detailed description of how temperature and moisture affect the composite can be found in 4.2.2 Other factors, Environment.

6.2.3.2 Material design

The composite is not only affected by the design of the final part, but also of the design of the material. The material design includes how the fibres should be oriented, the lay-up of the composite and the total number of plies in each direction. The orientation of the fibres influences the mechanical properties and the composite is stronger in the loading direction parallel to the fibres compared to perpendicular to the fibres. The fibres can be oriented in different ways, e.g. quasi-isotropic or unidirectional. Unidirectional laminates have all fibres oriented in one direction; while the fibres in quasi-isotropic laminates are oriented in 0°, ±45° and 90° directions. There are more information about fibre orientation in section Material properties in 4.2.1 Material and appendix A.1 Composites. The material should be designed so that the loads are applied parallel to the fibres, as it is the directions the fibres are strongest in. Composite structures is often applied to loads in many directions and quasi-isotropic fibre orientation is therefore a good option as the material then have the ability to take loads in several directions. This orientation is especially good when fasteners are used, as the structure then is able to carry the load. It is however not only the orientation of the fibres that should be considered when designing a material, the number of plies in each direction is also important. More fibres in each direction increase the strength of the fibres as each fibre only is able to take a certain amount of loading. On the other hand, the more plies that are oriented in one direction, the less will be oriented in another if the thickness is not changed, and the material will not become as strong in the other directions.

When designing composites it is preferable to design a symmetric laminate instead of an asymmetric laminate. This eliminates the extension-bending coupling that can reduce the effective stiffness of the laminate. In such way increases the material's deflection, the critical buckling load is reduced and the natural frequency of vibration is decreased. The composite will behave similarly with bending-twisting coupling, but the effects will be lesser (Mallick, 2007a). Symmetric and balanced laminates also minimises the risk for warpage and distortion on cool-down from elevated temperature curves (Campbell, 2010b) (U.S. Department of Defense, 2002). An example of what could happen when heating a symmetric and an asymmetric laminate is shown in Figure 35.

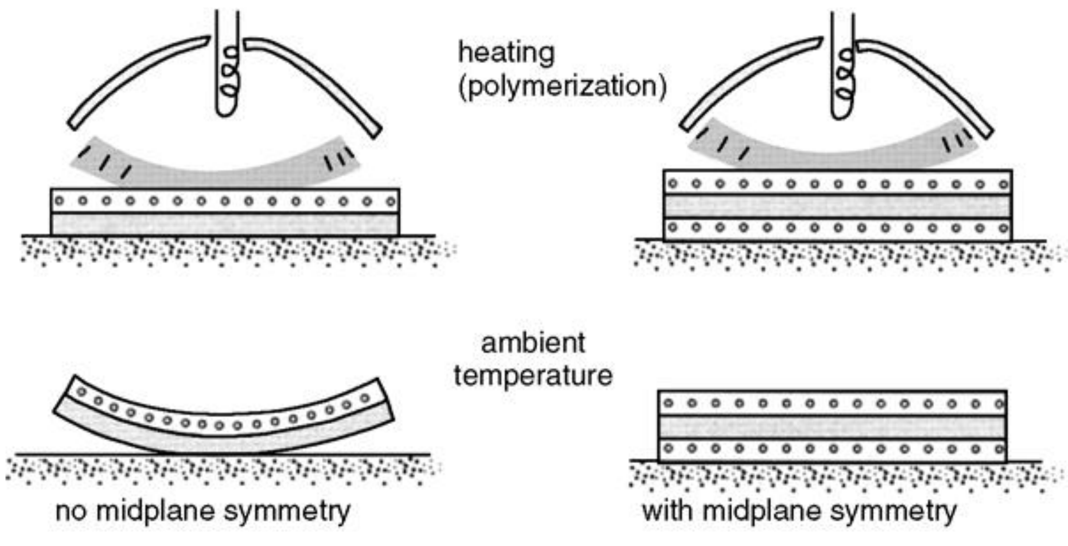

Figure 35. Effect of heated laminates (Gay, et al., 2002, p. 5.2.3.4)

6.2.3.3 Guidelines

In most cases there is no straightforward method for designing a composite laminate, if it not involves a simple structure, for example a rod or a column, with uniaxial loading. There are however three principal steps for designing a composite laminate (Mallick, 2007a):

1. Select fibre, resin and fibre volume fraction.

2. Select the optimum fibre orientation in each layer and the stacking sequence of the layers.
3. Select the number of plies needed in each direction; this determines the thickness of the part.

Gay et al. (2002) have set up three criteria that should be considered when designing for the ply configuration; these criteria do however not always work together:

1. The loading should be supported without deterioration of the laminate.
2. The deformation of the loaded piece should be limited.
3. The weight of the used material should be minimised.

The fibres and matrix should be selected so they have the ability to withstand the stress and strains that may be applied to it. The material should also be selected to ensure that the material can be used in environments with humid and varying temperature, where heavy-duty vehicles often are used. This is agrees well with the result from the tests done within this project, described in 6.1 Results and analysis of the tests. The tests show a reduction in modulus for both the tensile and bending tests for one respective two environmental cycles. This indicates that the environmental exposure can affect the material behaviour. It is the fibres that take the loads, and it is necessary to select fibres for the specific load and type of load. Carbon fibres are superior glass and aramid fibres in tensile loading, while glass fibres are better in compression loading. It is however not only possible to select a fibre material, there are different types of carbon with varying mechanical properties. The matrix should be selected so the glass transition temperature is about 30 to 40°C above the working temperature, in order to ensure that the material will not be affected by the temperature. The fibre volume fraction is another important factor to consider, the amount of fibres in comparison to matrix. If it is to low the mechanical properties are dominated by the matrix instead of the fibres. The fibre volume fraction should be about 60 per cent, in order to ensure the mechanical properties of the fibres and the matrix.

When the material is selected the fibre orientation should be decided. The fibres should be oriented according to the following:

- The fibres should be oriented with the principal load axes.
- In most cases a quasi-isotropic material is the best choice as it can bear loads in many directions; this lay-up should be used if the fasteners are used (Campbell, 2010b).
- Prevent warpage and distortion due to cool-down from elevated temperature cures by using symmetrical and balanced laminates. If it not is possible to design a laminate that is symmetric and balanced should the asymmetry or imbalance should be placed as near to the mid plane as possible. A laminate is symmetric if the plies positioned at an equal distance above and below the mid plane are identical. It is balanced if it has an equal number of $+\theta$ and $-\theta$ plies, where θ is measured from the primary load direction (U.S. Department of Defense, 2002).
- Place a 45° layer on each surface to minimise splitting when drilling (Campbell, 2010b) (U.S. Department of Defense, 2002).
- At least four distinct ply angles with a minimum of ten per cent of the plies in each angle. The angles of the plies should be selected so that the fibres are oriented with the principal load axes (U.S. Department of Defense, 2002).

And the layers should be stacked according to:

- Laminate properties are dependent on the stacking sequence of a laminate, but the relationship between the properties and the stacking sequence can vary. Any design application should therefore involve a compromise determination relative to the laminate stacking sequence (U.S. Department of Defense, 2002).
- To limit the interlaminar stresses should too many groups of plies in the same direction should be avoided (Gay, et al., 2002). No more than four plies should be grouped together if grouping of plies cannot be avoided. This can minimise the risk for delamination and creates a more homogeneous laminate (Campbell, 2010b) (U.S. Department of Defense, 2002).
- Fibre dominated laminates should be used if possible. A minimum of 10 per cent of the fibres should be placed in each direction to minimise the matrix and stiffness degradation (Campbell, 2010b) (U.S. Department of Defense, 2002).
- Avoid grouping 90° plies, they should be separated by a 0° ply or ± 45° plies where the loading direction is critical. This to minimise the interlaminar shear and normal stresses, multiple transverse fracture and grouping of critical plies (Campbell, 2010b) (U.S. Department of Defense, 2002).
- For strength controlled design homogenous laminate stacking sequences are used, i.e. the angle plies should be evenly distributed throughout the laminate thickness (U.S. Department of Defense, 2002).

6.2.4 Design of component

This section considers the actual design of the composite. As mentioned in section 4.2.1 Material, Material properties, the thickness of the composite one factor that affects the material’s resistance to fatigue; the thicker a laminate is the better is its resistance. The thickness of the part is determined by the number of plies, as described in chapter 6.2.3.2 Material design.

Mallick gives (2007a) examples of how simple composite structures can be designed. A tension member can have very high strength properties in the loading direction when the loads are applied parallel to the fibres. It is important to design so that the overall column buckles and local buckles can be prevented when designing a compression member. The optimum design of a compression tube is dependent on the lay-up design.

There are many factors that affect the design of a composite structure. The structures should be designed as modules instead of single parts; this in order to get a stronger structure that is less sensitive for example for fatigue and damages, and to reduce the number of machining and assembly operations. The assembly costs could be reduced in this way. It is however important to not design too complex structures as it will become difficult to manufacture and hard to inspect. Inspection is another important parameter when designing, as mentioned in 6.2.1 The design procedure. It is important in order to ensure the quality of the structure and for ensuring that it will not fail. In general are the thicker composite structures the better, as they become more resistant to impact damages, loads and fatigue. The thickness on the other hand increases the weight of the component.

There are two types of joints suitable for CFRP with a thermosetting resin, as described in appendix A.3.2 Joining: mechanical fasteners and adhesive bonding, with different advantages and disadvantages. Joints in some way are needed in order to join two parts together; to design a whole vehicle in one part would be, if not impossible, very complex and difficult to handle. Fatigue often occurs in the weak link of the composite, and as joints can act as such link this is important to have in mind when designing. According to Campbell (2010b) should the joints therefore be designed first, and then should the space between them be filled with laminate. There are issues with both types of joints. Mechanical fasteners risk causing galvanic corrosion if metals are used in the joints due to the difference in electronic potential between the carbon fibre composite and the metal. The metals will then corrode and wear out, and the joints fail. It is therefore of high importance to select a proper material in the mechanical fasteners when designing. In section 2.2.2.1 Mechanical fasteners, Galvanic corrosion more information about galvanic corrosion and issues with it can be found. Another difficulty with this type of joints is to transfer loads between the composite and the joint. The risk is that the loads only are transferred between the outer plies and not throughout the whole composite. When making holes for mechanical joints it is preferably to machine mould the holes after manufactured the composite, compared to forming the hole during the moulding of the composite part. The moulded holes can, according to Mallick (2007a) be surrounded by misoriented fibres, resin-rich areas or knit lines. The main issue with using adhesive bonding is the difficulty to design the joint in a way that ensures that the loads are transferred to all fibres, and not only to the bonded outer layers in the two parts. Delamination is another issue with this type of joint.

The surface finish is also necessary to consider when designing in composite materials. Ultraviolet rays can degrade epoxy resins, but this can be avoided by a good painting system covering the composite that protects the composite. Erosion or pitting caused by high-speed impact of rain or dust particles are other factors that can affect the mechanical behaviour of the composite, this can however be avoided by special surface finishes, e.g. thick rain erosion coatings (Campbell, 2010b).

6.2.4.1 Guidelines

It is possible to mould complex forms when designing in composite materials and the number of parts could be reduced compared to a metal structure. By reducing the number of parts the amount of processing work can be reduced (Gay, et al., 2002). It is however difficult to offer detailed guidelines for composite materials according to Campbell (2010b), but some are:

- Joints
    - Joints shall be designed first, then fill the space between with laminate. This because joints are a weak link of the composite (Campbell, 2010b).
    - Open holes should be avoided for compression loading, while filled holes should be avoided for tension loading (Campbell, 2010b).
    - Galvanic corrosion may be a problem and the material in the joints should therefore be selected so that the risk is reduced. Steel and aluminium are especially sensitive to galvanic corrosion. This can alternatively be avoided by ensuring that the metal and the composite not have direct contact, see 2.2.2 Joining.
    - There is also a risk for damages in the material when making the holes, which can cause degradation in the material. It is preferably to machine the holes after manufacturing the composite part, instead of integrating the holes during the manufacturing process, see 6.2.4 Design of component.
    - Skin-stiffening approaches need to be considered when designing the joints and the thickness and orientation of the laminate (Campbell, 2010b).
    - If adhesive bonding is used, ensure that the loads can be transferred to all the fibres in the composite, not only to the outer layers that are bonded together by the joint.

  - Adhesive bonding is the best choice for thin composites with well-defined loadings while mechanical fasteners are best for thick composites with complex loadings (Campbell, 2010h).
  - How efficient the loads can be transferred in an adhesive joint is very much dependent on the design of the joint (Campbell, 2010h). The design of this joint is therefore very important.
- Design as large structures as possible so that:
  - The number of parts can be reduced.
  - The number of joints is reduced.
  - The costs can be lowered thanks to fewer parts and reduced assembly time costs.
  - If the assembly requires far too complex tooling the potential cost savings can however be neglected (Campbell, 2010b) (U.S. Department of Defense, 2002).
- Avoid or minimise conditions that can cause peel stresses
  - Large abrupt laminate closures or cocured structures with significantly different flexural stiffness should be avoided.
  - Peel stresses occur in the weakest direction of the laminate (Campbell, 2010b) (U.S. Department of Defense, 2002).
- Finite element analysis
  - In regions of high stiffness gradients, e.g. around cut-outs and at ply and stiffener drop-offs, Finite Element Analysis (FEA) must be used. Premature failure can occur if the definition or management of stresses around discontinuities are improper (Campbell, 2010b) (U.S. Department of Defense, 2002).
  - FEM analysis can also be used to ensure the strength and the stress distribution throughout the composite. In paragraph 4.1.3 Avoiding fatigue, FEM is described more in detail.
- Thickness
  - The thickness tolerances of the part vary directly with the part thickness, as thick parts require higher tolerances (Campbell, 2010b).
  - The thicker a laminate is the better resistance it has to impact damage and fatigue, see 4.2.1 Material.
- Surface design
  - The risk for moisture absorption in the matrix can be minimised by coating the material in a proper surface finish.
  - Epoxy matrixes can be degraded because of ultraviolet ray and by using a painting system to cover and protect the composite this can be avoided (Campbell, 2010b).
  - Surface finishes, e.g. thick rain erosion coatings can be used to avoid erosion or pitting caused by high-speed impact rain or dust factors (Campbell, 2010b).
  - The surface finish can also protect the composite from damages etc.

7 Discussion

It is relatively easy to find information about composite material in general, but as there are large variations between the different materials it is sometimes difficult to find information about carbon fibres composites, especially combined with specific matrices. This varies between the areas studied in this report, but for fatigue glass fibres are mostly described in literature. As glass and carbon fibres behaves differently in many ways, but similar in others, the information about glass fibres' fatigue behaviour cannot be used for carbon fibres. It is also relatively difficult to find data about composite materials and which loads they can withstand; the main reason for this is probably because so many factors affect the material properties.

Fatigue is one area that is hard to find information about, particularly how the material behaves under different loadings and the cycle time for CFRP. As far as I can tell few studies are done for high cycling loads, and little data is therefore available. When reading about composites, the literature is either covering the area quite general or focuses on a specific material. The reason for little data available in literature is either because there is no data, or the data is not published. It is hard to tell how much information that actually is known, but it is however necessary to perform tests in order to better understand how composite materials behaves, and mainly for specific combinations of CFRP.

There are many opinions in literature of whether fatigue is a problem or not. Some mean that fatigue is the main reason for failure in composites, other that composites are not sensitive to fatigue. It may be possible that both opinions are right, as the fatigue behaviour of composite materials is different depending on the loading mode, e.g. bending, tensile or compression. This is rarely mentioned in literature; fatigue is rather mentioned as such and not related to the loading type. This makes it hard to draw any conclusions of which loadings that are critical to fatigue. It was not possible to test fatigue within the time frame of this project and it is difficult to tell based on literature whether fatigue is a problem or not. In order to validate this test should be necessary to do. I believe fatigue may be a problem for certain loadings but not for others and especially for multiple or variable loading modes, and it is of course depending on the orientation of the fibres. Fatigue is therefore important to have in mind when designing, but it is not necessary a problem. Temperature and moisture are affecting the material behaviour; therefore can the risk for fatigue increase when these environments are present. The probability that other issues occur in general is higher.

The aim of the design guidelines was to give the reader an understanding of how to design in carbon fibre composite materials and the factors that are important to consider. Many of the guidelines are based upon what I have read in literature and information gathered in the earlier parts of the project. It is in general difficult to find information about how to design in composite materials, because of the many factors that affect the design. As I have been interested in a specific material, carbon fibre reinforced epoxy; it is even more difficult to find information, as much literature concerns composite material in general or polymer matrix composite in general. It is not an easy task to give directions for how to design in composite materials, as so many factors affect the designing. The design guidelines stated in this project shall therefore not be seen as a fully covering document, it is more of an indication of what is necessary to consider. There may be other factors that affect the designing, dependent on the material, environment and applied loading. The guidelines are not specifically focusing upon how to design according to fatigue, and the reason for this is that other parameters seem to be more critical, and when reading about designing fatigue is rarely mentioned. As described earlier in this chapter a reason for this may be that depending on the loading mode fatigue is not necessary a problem.

The aim of the project changed during time, in order to reduce the width of the project and to better fulfil Scania's need. This resulted in less time and effort could be laid on the design guidelines, which the new aim focused upon. The literature review could however be kept, as the information still was relevant for the project. If the changes would have been decided earlier the project could have been improved by covering more aspects. I am however pleased with the result, and even if more time and effort could have been laid on the design guidelines if the aim would have been determined earlier, it is impossible to cover all aspects of designing in composite materials.

The tests show a small reduction in modulus for both the tests. It is the specimens cycled in the VDA cycle and the specimens in the hydrothermal cycle with salt that show a decrease in modulus for the static bending tests. The tensile tests show a reduction in the modulus for the specimens in the hydrothermal cycle with salt. The other mechanical results are not affected at all. The decrease for the modulus is very small in comparison to the reference, but this can however be an indication of what would happen if the specimens had been cycled for a longer time period. As this reduction is very small and relatively few specimens were tested it is difficult to tell if this was just a coincidence. But since both the static bending and tensile shows a reduction in the modulus for the hydrothermal cycle with salt, the probability that this cycle affects the specimens in other cases too is high. The method for the bending test is more sensitive than the method for tensile, this because the bending affects the fibres in more ways, not only in one direction as for the tensile test. The specimens for the bending are also smaller with more cutting edges in relation to volume; the specimens then saturate faster. The damage for static bending tests are different compared to tensile. The composite's interface can have larger impact on the bending test and this could be the reason why the VDA seems to have affected the specimens for bending and not for tensile. It is however difficult to make any clear conclusions about this, especially because the size of the specimens is very different. If the specimens would have had the same size it would have been easier to draw conclusions about how and if the size affects the specimens in the different environmental cycles. In order to better understand how the different environmental cycles affects the material behaviour and to compare the results between tensile and compression tests, more tests need to be done. In this project the cycles were progressed for a relatively short time, and longer time periods should be necessary to test, especially because those specimens are not saturated. It is however positive that no significant reduction in material strength can be seen after three weeks in the climate chambers. This indicates that the issue with an absorbing polymer in the composite may not be such a large problem.

The only conclusion that can be drawn from the tests is that the exposure to different environments with varying temperature and moisture content has affected the mechanical properties for the used composite material. It is not possible to draw any conclusions whether static bending or tensile is the most critical. In order to do so is it necessary to study the material behaviour more in depth.

8 Conclusions

This project aimed to answer the research questions set up in the initial phase of the project, as stated in section 1.3 Aim:

Which issues, related to material properties, production, processing and usage, may occur when implementing carbon fibre reinforced plastics, CFRP, in the rear of a bus?

What design guidelines can be formulated in order to handle those identified issues in the product development process?

I have managed to answer both research questions throughout the project. The issues were identified based on literature and the discussions held during meetings with my supervisor and other persons at Scania. The identification of the issues leads to further investigation of fatigue and how it affects CFRP. Design guidelines were formulated in order to handle all four of the identified issues. The guidelines states important parameters to consider when designing in carbon fibre composites.

Which issues, related to material properties, production, processing and usage, may occur when implementing carbon fibre reinforced plastics, CFRP, in the rear of a bus?

There are many issues related to the implementation of CFRP in the bus chassis. Galvanic corrosion, fatigue, delamination and joining were identified as the four most critical problems. All four problems have significant impact on the material behaviour of composites. Galvanic corrosion can cause degrading of strength in mechanical fasteners with the risk that the product fails. When the layers are separated from each other it is called delamination, and this is one type of damage in composites. The mechanical strength is then decreased, as the load cannot be transferred between the fibres and in the fibres loading direction. Many problems are related to joining, but it is dependent on the type of joint that is used. When using mechanical fasteners there is a risk for galvanic corrosion, if the wrong type of metal is used in the joint. Delamination can occur when machining the holes and there is a risk for stress concentrations around the bold holes. Delamination can also be a problem for adhesive bonding. With this type of fasteners it is difficult to ensure that the loads are transferred to all fibres in the composite, and not only the outer layers. Joints are often the weak link of the composite and failure due to fatigue often occurs in those places. Fatigue is weakening the material due to cyclic loadings and the material risk to fail because of this.

There are other issues when manufacturing, processing and using composite materials. Those mentioned above are identified as the most critical in this case. The main difficulty when implementing CFRP in the heavy-duty industry is the material's different behaviour compared to conventional materials. Even if the strength and stiffness are similar, it is much more complex to design in CFRP as the fibre orientation, type of matrix, selection of manufacturing method etc. affects how the material will response to loadings.

What design guidelines can be formulated in order to handle those identified issues in the product development process?

The design guidelines were formulated based on all four of the identified issues as all of them affect the mechanical properties of carbon fibre composites.

Fatigue was selected as the area to further focus upon. As it weakens the material and there is a risk for failure, it is important to the design in a way to minimise the risk for fatigue. Fatigue is affected by the selection of material, the material design, manufacturing process and the design of the structure. As many factors affect the fatigue behaviour it is a difficult task to write clear guidelines of how to design in composite materials, and to ensure that they are adoptable to most constructions. Fatigue was however not identified as the most critical parameter when designing in composite materials, but by designing to avoid fatigue other issues may be avoided.

The fibres and matrix should be decided first, followed by the fibre orientation and stacking sequence. There are plenty of different fibres and matrices and they can be combined in many different ways. This results in a variety of materials with different properties. The environment can decrease the mechanical properties of CFRP. When applied to temperature changes and humid environments there is a risk for degrading material properties, and then also their ability to withstand fatigue and other loadings. This type of environment is common for heavy-duty vehicles as they are often used in humid environments with changing temperatures. The material therefore has to be selected both for its mechanical properties and depending on the environmental conditions.

How the fibres are oriented and the plies are stacked are another factors that affect the mechanical behaviour of the composite. The fibres should be oriented in the loading direction to be able to carry the load. The more fibres in the same direction the stronger the material is in that direction, but the strength in others decreases. The fibre direction and stacking sequence need to be organised in a way to carry the different loadings.

High quality parts are important for fatigue sensitive composites, this because voids and other damages can act as sites for damage and cause fatigue. It is therefore necessary to select a method that can deliver a material with the required quality, at the same time as the parts needs to be manufactured in high volumes to a relatively low price.

The design of the component or structural part is the actual design of the composite. The thicker a part is the better resistance to fatigue and impact damage, and the risk for delamination decreases. The parts should be designed as large as possible, to reduce the number of parts and the number of fasteners. Joints are another important aspect when designing in composite materials, and they should therefore be designed first. By designing large structures some of them could be avoided, but they are often acting as the weak link in the composite, and it is often here fatigue occurs. Galvanic corrosion was another of the identified issues, and the risk is that the mechanical fasteners wear away due to this. This can be avoided by carefully selecting a proper material in the joints or by using electrical isolators. The best way to avoid problems with both joints and galvanic corrosion is to design in a way so that the number of joints can be minimised.

8.1 Recommendations

The implementation of carbon fibre reinforced plastics in the production of heavy-duty vehicles is not an easy task. The material is in many ways different from steel, both in mechanical properties and behaviour as well as the designing of the material. In order to successfully implement the material in the production there are several things that need to be done. It is necessary to gather more knowledge about using CFRP, to educate the designers of how to think when designing in this type of material and to educate the workers in the production of how to handle the material. A manufacturing process suitable for Scania’s need is necessary to select, and the production has to be changed to suit this process. There are of course much more to do, and these design guidelines focus therefore on recommendations in the near future and how the result from this project could be improved.

8.1.1 Testing

More tests need to be done in order to better understand how CFRP behaves under different loadings and exposure to different environments. Fatigue needs to be tested, as this was not possible to do within the project. In this way it would be possible to understand if fatigue actually is a problem. Different loadings affect composite material differently depending on the material combination, lay-up, fibre orientation etc. Other loadings would therefore be interesting to test for different material combinations. Those tests would be especially interesting to combine with different environmental conditions.

The specimens in this project were exposed to three different cycles and according to the moisture absorption data it seems as the specimens exposed to the hydrothermal cycle and submerged in the NaCl-solution and the VDA were affected the most. In order to validate if it is the salt that degrades the composite or the submerging in water more tests are necessary to do. Different matrices absorb moisture differently and it may be necessary to do the previous test all over again, to ensure that the same material is used and the results comparable. Exposure to other environmental conditions would also be interesting in order to better understand the material behaviour. CFRP may be exposed to chemicals during manufacturing or usage, the resistance against chemicals is because of that another thing to test.

The results from the tests could be gathered in a database with information about certain fibres, matrices, lay-up, fibre orientation etc., to be able to use the information when designing in composite materials. When implementing composite materials in the vehicle manufacturing, it may be good to limit the number of material combinations, fibres and matrices, and the design of the material. The reason for this is because each new combination results in a new material with different mechanical properties that need to be tested.

8.1.2 Design guidelines

The design guidelines are very general and it is therefore necessary to change and adjust the guidelines to suit Scania’s need and the purpose of the different departments. This as the products and parts may have different requirements depending on purpose and application.

Consultation with design engineers needs to be done, in order to validate if the guidelines are relevant for the design process and how they can be changed in order to better suit their specific need.

There is a need for more information and knowledge about how fatigue affects CFRP, much information about fatigue for composite materials considers glass fibres, reinforced with e.g. epoxy. As glass fibres and carbon fibres have different properties the information is not possible to use. The reason for this may be that either carbon fibre composites are not affected by fatigue and therefore not considered, or the information exists at other companies but is not available for the public. More information is therefore necessary to gather, also for other loadings than fatigue.

Joining is just briefly considered in the design guidelines. The design of these joints and the used material is something that is important to focus on in further studies. If mechanical fasteners are used the material is of high importance as the risk for galvanic corrosion is high. Which materials that can be used together without the risk for galvanic corrosion in the specific environments are important to consider. How the joints are affecting the strength of the composite is another important aspect to focus on in further studies, as the mechanical properties of the composite may decrease.

Galvanic corrosion, delamination, joining and fatigue were identified as the four most critical issues with CFRP. Those problems may have significant impact on the mechanical properties of the composite and it is therefore important to find a way to handle those issues in order to minimise their impact on the composites. This may however be a later stage in the process of implementation composite materials in the heavy-duty industry but may be good to consider relatively early, for example can the problem with joints and galvanic corrosion be reduced if the number of joints is limited and it is therefore an important design parameter.

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10 Appendix

A Literature review

A.1 Composites

A.2 Manufacturing methods

A.3 Processing

B Weight of specimens before and after environmental exposure

C Salt submerging in hydrothermal cycle with salt

D Calculations static bending

E Results from tests

E.1 Static bending

E.2 Tensile

A Literature review

This literature review has been done in order to receive a better understanding of composite materials and their properties. It has been created in order to ease the coming work and to start the thought process about the use of lightweight materials. This project will focus on carbon fibre composites, the manufacturing, processing and usage of them. The literature review is divided into four categories, composites, manufacturing of composites, processing of composites and problems that may occur.

The material that probably will be used by Scania in the future and the material this project will focus upon are continuous carbon fibres reinforced with a thermoset matrix, such as epoxy or vinyl ester. Other materials will be mentioned, but the main focus will lie on those.

A.1 Composites

Combining two creates a composite or more materials into one and a material with better properties than the individual materials can be achieved. The composite consists typically of one or more fillers, reinforcement, in a certain matrix (Chung, 2004). The reinforcement is usually fibres, e.g. carbon. It is the reinforcement that provides strength and stiffness, and is in most cases harder, stronger and stiffer than the matrix (Campbell, 2010c). The reinforcement can be in layers, but also as yarn or woven or as short fibres without specific organisation (Johannesson, 2013). The matrix, in a polymer or metal composite, transmits loads from the matrix to the fibres through shear loading at the interface (Campbell, 2010c). By using different materials as fibres and matrix it is possible to receive a composite with different properties, in order to get a material well suitable for the specific purpose. The most common way to classify fibre-reinforced composites is according to the matrix used: polymer, metal, ceramic, or carbon (Daniel & Ishai, 1994).

There are many advantages with using composites instead of conventional materials. The weight can be reduced, the tooling costs lower, the number of parts could be reduced and fewer assembly operations could reduce the costs for acquisition and/or lifecycle costs for composite materials. These advantages are sometimes diluted as the costs for raw material, fibres, prepreg and auxiliary material used in fabrication in combination with composite material his high. Conventional structural materials have usually a lower cost for raw material but the cost for tooling, machining and assembly is on the other hand high (Daniel & Ishai, 1994). Corrosion is a common problem within the marine industry and those problems can be avoided by using composite materials. This thanks to the material properties and their good corrosion resistance. The life length is longer for composite materials and they require less maintenance than many other materials with less corrosion resistance (Campbell, 2010c). Other advantages with composites compared to conventional materials are:

- Lower weight
- Possible to tailor the lay up for optimum strength and stiffness
- Improved fatigue life
- Corrosion resistance
- With good design practice it is possible to reduce cost due to fewer detail parts and fasteners

And some disadvantages:

- High costs for raw material
- Usually high costs for fabrication and assembly
- Adverse effects of both temperature and moisture
- Poor strength in the out of plane direction where the matrix carries the primary load
- Susceptibility to impact damage and delamination or ply separations
- More difficult to repair composites compared to metallic structures (Campbell, 2010c)

A composite with a metal matrix is not relevant as the purpose of changing to composite material is to reduce the vehicles weight, and with a metal matrix is such a high reduction not possible. Ceramic matrices are only used for very specific purposes, and are very well suited for high temperature applications (Daniel & Ishai, 1994). Another kind of composite materials are sandwich-structured composite, where two sheets of material are joined together by another material, e.g. carbon fibres in the sheets and some kind of foam between the sheets, to receive different properties (Drechsler, et al., 2009).

A.1.1 Fibres

Carbon fibres have high strength and stiffness. It is only boron and carbon that have those combined properties; the other types of fibres have either high strength or high stiffness, not the combination (Daniel & Ishai, 1994). The focus in this project will lie on carbon fibres, as they are the most suitable for the specific purpose; to replace the steel in the chassis of the buses. Other fibres are therefore only mentioned. Table 1 below shows advantages and disadvantages of some common fibres.

Fibre	Advantages	Disadvantages
E-glass, S-glass	High strength	Low stiffness
	Low cost	Short fatigue life
		High temperature sensitivity
Aramid (Kevlar)	High tensile strength	Low compressive strength
	Low density	High moisture absorption
Boron	High stiffness	High cost
	High compressive strength	
Carbon (AS4, T300, C6000)	High strength	Moderately high cost
	High stiffness	
Graphite (GY-70, pitch)	Very high stiffness	Low strength
		High cost
Ceramic (silicon carbide, alumina)	High stiffness	Low strength
	High use temperature	High cost

Table 1. Advantages and disadvantages of reinforced fibres (Daniel & Ishai, 1994, p. 2.9.1)

The fibres can either be short or continuous. Short fibres, also called discontinuous fibres, can be either all oriented along the one direction or in random directions. Continuous fibres composites are the most efficient when it comes to stiffness and strength. The reinforcement in those composites consists of long continuous fibres, where all can be parallel, oriented at right angles to each other, or oriented along several directions (Daniel & Ishai, 1994).

Materials can be either isotropic or anisotropic. An isotropic material has the same properties in all directions. An anisotropic material on the other hand has different properties in all directions at one point in the material. Bulk material, e.g. metal and polymers, is normally treated as isotropic material, while composites are anisotropic (Campbell, 2010c). A composite material is usually anisotropic if the fibres are oriented along one direction. (Daniel & Ishai, 1994).

Fibre composites commonly consist of many layers, and the fibres in continuous-fibre composites laminated materials are normally oriented in directions that will enhance the strength in the primary load direction (Campbell, 2010c). Unidirectional laminates fibre reinforced polymers have a fibre direction of 0° and is very strong and stiff in this direction, but are very weak in the 90° direction as the load must be carried by the polymer matrix that is much weaker (Campbell, 2010c). By rotating the fibres in certain angles can specific stiffness and values of strength be achieved (Chung, 2004). The orientation of the fibres in the matrix is the factor that mainly influences the fibres' performance. The most optimal utilisation is achieved when the fibres are placed in the direction of the load, small deviation can reduce the strength and stiffness of the composite (Drechsler, et al., 2009). According to Campbell (2010c) may this way of placing the fibres work for some structures, but it is usually necessary to place them in different directions, e.g. 0°, +45°, -45°, 90°, in order to balance the load-carrying capacity (Campbell, 2010c). When a laminate have an equal number of layers in the 0°, 90°, 45°, -45° directions it is called a quasi-isotropic laminate. It carries loads in all four directions, and is therefore the preferred orientation (Campbell, 2004b). There are other factors that affect the performance of the composite, such as fibre volume fraction, the stiffness of the matrix, damage tolerance, single ply thickness, voids, fibre matrix interface, moisture and media, temperature, holes and cut-outs (Drechsler, et al., 2009).

A.1.1.1 Carbon fibres

The properties of carbon fibres are equal to steel, but with lower density. As mentioned in Table 1 above, have carbon fibres high stiffness and strength, and the fibres have also good thermal stability and when combined into a matrix is the fatigue resistance excellent (Chung, 2004). The combination of properties is superior, but the material is much more expensive than both glass and aramid. (Campbell, 2004b). Carbon fibres have poor abrasion resistance, and are attacked from some acids, and undergo galvanic corrosion when the material have contact with certain metals and allows (Chung, 2004).

Carbon fibres are commonly combined with a polymer matrix, and are then often called CFRP or carbon fibre reinforced plastics. It is possible to receive a high performance material with a weight reduction of more than 50 per cent compared to high strength steel by using CFRP (Drechsler, et al., 2009). The strength of CFRP is as high as for high strength steel, the stiffness high and the density is 40 per cent lower than aluminium. The material's fatigue and creep resistance are good, and by using laminate orientation can the material be designed to be tougher and more damage tolerant than metals. The chemical and corrosion resistance are also good as well as the dimensional stability, and compared to metals the vibration damping is ability excellent. The electrical resistivity is low, and the thermal conductivity is high. Composites based on carbon fibres have low energy-absorbing capacity, poor resistance to transverse impact loading and the plies have a tendency to separate from each other in the laminate (Chung, 2004).

It is possible to get carbon fibres with a wide range of different strength and stiffness. Campbell (2004b) classifies them in three categories due to strength and stiffness; high strength, intermediate-modulus or high modulus fibres (Campbell, 2004b). Chung (1994a) classifies carbon fibres a slightly different way, also in three categories: general-purpose (GP), high-performance (HP), activated carbon fibres (ACF). General-purpose fibres have low tensile strength, low tensile modulus and low cost, and high-performance have relatively high strength and modulus. Activated carbon fibres have a large number of open micropores, which acts as adsorption sites, the material has therefore a good adsorption capacity, comparable to activated carbon but the shape of the fibres allows the adsorbate to get to the adsorption site faster (Chung, 1994a). The fibres have also specific names depending on properties; AS4, T300 and C6000 are some (Daniel & Ishai, 1994).

Carbon fibres and graphite are both names used to describe carbon fibres. The main difference between them is the content of carbon. Carbon fibres consists of typically 95 per cent carbon, and are carbonised at circa 1000 to 1500°C, while graphite fibres contain about 99 per cent carbon, and are first carbonised and then graphitised at temperatures between 2000°C and 3000°C. The graphitisation process generally results in a fibre with higher modulus (Campbell, 2004b).

Carbon fibres can be made from rayon, polyacrylonitrile (PAN) or petroleum-based pitch (Campbell, 2004b). The best combination of properties is produced of PAN-based fibres (Campbell, 2004b), which is a form of acrylic fibres (Walsh, 2001). Rayon is rarely used today, because of higher cost and lower yield compared to carbon fibres. Petroleum-based pitch fibres are mainly used to produce high- and ultrahigh-modulus graphite fibres, but were developed as a lower cost alternative to PAN. Carbon fibres are produced as untwisted bundles, so-called tows, with thousands of fibres, common is one, three, six, 12 or 24 thousand fibres. In order to improve the adhesion of carbon fibres to the polymer matrix are they normally surface treated immediately after manufacturing. Sizing is also often applied in form of thin film, to improve handleability and protect the fibres during weaving and other handling operations (Campbell, 2004b). Depending on the processing temperature it is possible to receive carbon fibres with different stiffness and strengths. To get high strength and high stiffness carbon fibres it is necessary to process the material between 1200° and 1500°C. Ultrahigh stiffness graphite fibres are processed at temperatures between 2000° and 3000°C. The increase of stiffness is achieved at the expense of the strength (Daniel & Ishai, 1994). The majority of all carbon fibres are made from PAN precursor (Walsh, 2001).

Polymer matrix composites are today used for lightweight structures, and carbon fibre composites are for example used within the aerospace, automobile (e.g. formula 1 cars), and offshore industry but also in sporting equipment (Chung, 2004) (Drechsler, et al., 2009).

A.1.2 Matrices

The matrix is both maintaining the position and orientation of the fibres as well as protects them from possible degrading environments (Chung, 2004) (Case & Reifsnider, 2003). In polymer and metal composites is the matrix transiting loads from the matrix to the fibres through shear loading at the interface (Campbell, 2010c). The most commonly used matrices are polymer matrices, and are reinforced with glass, carbon, aramid or boron fibres. These composites are used at relatively low temperatures. Other matrices are metal and ceramic matrices and carbon/carbon composites. The metal matrices composites consist of metals or alloys and are reinforced with boron, carbon or ceramic fibres. The softening or melting temperature for the matrix limits the maximum temperature for metal composites. The matrix in ceramic matrix composites is ceramics as well as the fibres. This composite is well suited for very high temperature applications. The last one, carbon/carbon composites, is carbon or graphite matrix reinforced with graphite yarn or fabric. The properties are unique with relatively high strength at high temperatures in combination with low thermal expansion and density (Daniel & Ishai, 1994).

A.1.2.1 Polymer matrices

Polymers have low strength and stiffness (Campbell, 2010c), but by combining polymers with fibres it is possible to receive higher strength and stiffness than the polymer itself has (Johannesson, 2013). Due to high strength and low density, are fibre-reinforced polymers the most dominate among polymer structural materials (Chung, 2004). Polymers are divided into two different types, thermoset or thermoplastic depending on the matrix. Thermosetting matrices are the most common polymer matrix today, where epoxy is the most used (Daniel & Ishai, 1994), but thermoplastics are developing rapidly. Some reasons why thermosetting matrices are popular are the low melt viscosity, the fibre impregnation is good and the processing temperatures are relatively low, and they are cheaper than thermoplastics (Case & Reifsnider, 2003). There are a number of advantages of using composites with a thermoplastic matrix instead of thermoset. The manufacturing cost is lower and the performance is higher thanks to high damage tolerance, good hot and wet properties and high environmental tolerance. Neither is cure needed for thermoplastics. On the other hand there are disadvantages, such as limited processing methods, high temperature during processing, high viscosity, prepreg and the treatment of fibre surface is less developed than for thermosetting matrices (Chung, 2004). Hot forming and injection moulding fabrication methods are thermoplastics more compatible with than thermosetting matrices. Thermoplastic can be applied at temperatures up to 400°C (Daniel & Ishai, 1994). Polymer matrix composites require a relatively low fabrication temperature, therefore are they easier to fabricate than composites with metal, ceramic or carbon matrices, independent of if it is a thermoset or thermoplastic. The processing temperature for fabricating thermoset is usually within the range from room temperature to about 200°C, and for thermoplastics is the range of the processing temperature typically from 300°C to 400°C. All materials that are based on polymers are unable to withstand high temperatures (Chung, 2004).

A.1.2.1.1 Thermoset

As mentioned earlier are thermosetting matrices the most popular matrix system for composite materials. The material has good mechanical properties when operating in hot and moist environments, it is easy to process and have good adhesion to many fibres, and the material cost is low (Case & Reifsnider, 2003). Thermosetting plastics are not possible to reshape, it is a rigid cross-linked material that at high temperatures degrade rather than melt (Chung, 2004). Before curing has the thermoset resin low viscosity that allows easy impregnation of the fibre. When the curing is done is the material no longer possible to melt (Drechsler, et al., 2009). There are different types of thermosetting matrices; some of them are mentioned below (Chung, 2004):

- Polyester
- Epoxy
- Vinyl ester
- Polyimide

- Phenolic resins

Polyester

According to Chung (2004) are unsaturated polyester resins one of the most common matrices in the manufacturing of composite components. The material is used in quick-curing systems for commercial products (Daniel & Ishai, 1994), as well as for large, single-piece components e.g. boat hulls, especially within the marine industry. Standard polyester resins have lower tensile strength than many others of the thermosetting resins and are limited in terms of the maximum operating temperature. Other types of polyester are available, with different properties e.g. superior strength or resistance to acidic environments. Composite parts based on polyester are generally manufactured using hand-lay up or spray-up techniques. Care has to be taken in order to ensure that exothermic heat generation does not damage or degrade the composite during manufacturing (Chung, 2004).

Epoxy

The most widely used polymer matrix for carbon fibres is epoxy (Chung, 2004) (Daniel & Ishai, 1994). It is also the most important (Drechsler, et al., 2009). The material is common in high performance continuous fibre composites (Chung, 2004). Daniel and Ishai (1994) classify epoxy into two categories, which are used in different environments depending on temperature and moisture variations. The different categories are: those that are cured at lower temperature (120°C) and used in components exposed to low or moderate temperature variations, e.g. sports equipment, and those that are cured at higher temperature (175°C). The latter are used in high performance components and are exposed to high temperature and moisture variations, e.g. in aircraft structures (Daniel & Ishai, 1994). The curing process involves addition of a hardener and possibly an accelerator, and the temperature cycle between 60 and 180°C (Chung, 2004). It is the combination of mechanical properties, corrosion resistance, dimensionally stable, exhibits good adhesion and relatively inexpensive that gives the material good properties. Compared to polyester are the mechanical properties and water resistance of epoxy superior, and the shrinkage during curing is lower for epoxies. Uncured epoxy resins in the liquid state have low molecular weight and the molecular mobility is high during processing. This facilitates the epoxy to spread quickly on the surface of e.g. carbon fibres (Chung, 2004). Epoxy is the most common material for high-performance composites and adhesives. It is common that commercial epoxy matrices and adhesives contains of one major epoxy and one to three minor epoxies and one or two curing agents, even if commercial epoxy could be as simple as one epoxy and one curing agent. The minor epoxies are added to provide viscosity control, improve high-temperature properties, lower moisture absorption or improve toughness (Campbell, 2004c). Epon, Epi-rez, D.E.R., Epotuf and Araldite are all trade names of epoxy (Chung, 2004).

There are several types of epoxy, and the major used epoxy for many commercial composite matrix systems are DGEBA (diglycidyl ether of Bisphenol A) and TGMDA (tetraglycidyl methylene dianiline) also known as TGGDM (tetraglycidyl-4,4"-diaminodiphenymethane). They are common within aerospace. DGEBA is the most widely used epoxy type, which is often used for filament winding and pultrusion because it is available as a liquid at several viscosities, and can be either a solid or a liquid. TGMDA is the base resin used in a majority of the commercial epoxy matrix systems. It has high strength, high rigidity and elevated temperature resistance. It is also available in a variety of viscosity, and is sold commercially as MY-720 and MY-721. In adhesive systems, where toughness is an important factor, mix suppliers DBEBA and TGMDA to help provide more flexibility in the cured adhesive (Campbell, 2004c).

Vinyl ester

Vinyl ester is often chosen because of their cost, ease of production and the material's resistance to wet environments (Case & Reifsnider, 2003) Vinyl ester has mechanical properties that are superior to those of polyester, and the material's resistance to water and chemical attacks is excellent (Chung, 2004). The material has similar chemical properties to epoxy, and can be used at approximately the same temperatures as epoxies. Vinyl esters are mainly used for commercial applications and are rarely used for high performance composite materials because the lower properties compared to epoxy (Campbell, 2004c). It is used in for example underground pipes, tank liners, and storage tanks (Chung, 2004).

Polyimide

Polyimides are becoming more important for higher temperature applications (Chung, 2004). According to Chung (2004) is polyimide developed to withstand 316°C, but Daniel and Ishai (1994) say that the material is used for high temperature applications, up to 370°C. Polyimide is more expensive than epoxies, because of higher curing temperatures and longer cycles. Composites that are made from polyimide prepreg are generally brittle at room temperature, but significant improvements in toughness are achieved in new material formations. The material is used for aerospace applications, as its hot-wet properties are attractive. One type of polyimide is PMR-14, which is used for jet-engine cowlings, ducts, compressor blades, flaps and fairings (Chung, 2004).

Phenolic resins

Phenolic resins were more used before than today, polyesters and epoxies have in large parts replaced the material. When high temperature stability and fire resistance are of very high importance are the material still used, for example within the marine industry, including internal bulkheads, decks and certain finishing. The curing process involves significant production of water, often resulting in the formation of voids within the volume of the material. Phenolic resins have a tendency to absorb water in damp or watery conditions have limited their widespread application. The material is also used as adhesive in plywood and phenolic moulding compounds is used household appliances, and in automotive, aerospace and electrical industries (Chung, 2004).

A.1.2.1.2 Thermoplastics

The thermoplastics are possible to reshape as they become soft at high temperatures. This is however only possible a limited number of times, as multiple reprocessing can degrade the resin (Campbell, 2010e). Many thermoplastic composites (e.g. carbon-reinforced PEEK) have good resistance to impact loading, and are therefore suitable for use in high performance engineering applications. Because of thermoplastics greater ductility and processing speed compared to thermosetting matrices, and the fact that thermoplastics are able to withstand high temperature have the material become more important. The reason for higher processing speed is because thermoplastics softens immediately when heated above a certain temperature, and the soften material is easy to shape. In contrast to thermosetting resins is the curing of thermoplastics gradually. Components made with thermoplastics can be possible to join thermal and to repair, but also recycling (Chung, 2004). The viscosity of the molten material is relatively high and the wetting is not as easy as for thermosetting materials, which results in lower mechanical properties. On the other hand is the handling of thermoplastics easier as the storage time for the system is longer.

Special technologies are needed because the high viscosity and melting temperature. Some thermoplastic system can be transformed into thermoset systems by using high-energy radiation and network activators (Drechsler, et al., 2009).

Due to high material costs and the need of mass production has the use of thermoplastic for high-performance composites been limited until now. Drechsler et al. (2009) believe that the use of pre-consolidated organic sheets is the most promising, this because sheets with complex structures can be produced and as it is possible to weld thermoplastics that are comparable to metal (Drechsler, et al., 2009).

There are several thermoplastics that are used as matrices, Drechsler et al. (2009), mention polypropylene, polyamide, PEEK, and polyetherimide. Chung (2004) mentions, PEEK, PI, PES, PEI, and PPS. The focus in this chapter will lie on the following four thermoplastics:

- Polyetheretherketone (PEEK)
- Polyetherimide (PEI)
- Polyphelylene sulphide (PPS)
- Polyamide (PA)

Polyetheretherketone (PEEK)

PEEK, also polyetheretherketone, is extremely expensive compare to many of the thermosetting matrices. As a reason of this are PEEK composites considered for use in high performance engineering applications, such as aerospace components. PEEK-components are capable of absorbing considerable energy before incurring damage. This is most evident under impact conditions as the incident energy for a delaminated area may be three times smaller than in a comparable epoxy-based composite. Carbon fibre PEEK has high interlaminar fracture toughness, and superior fatigue properties. Composites based on PEEK require high processing temperature (typically 380-400°C), and to ensure that the resulting degree of crystallinity is not to high is rapid cooling rate suggested (Chung, 2004).

Polyetherimide (PEI)

PEI has superior resistance to impact loading and higher interlaminar fracture toughness than most epoxies. As the material is not possible to reshape the material have lower solvent resistance, which is a limitation if the composite based on this type of polymer is to be used in aggressive environments (Chung, 2004). Processing the material is easy (Vaidya, 2011).

Polyphelylene sulphide (PPS)

PPS is used in electrical insulation, specialty membranes, and gaskets. Within the automotive industry is the material for example used in brake sensors, connector body and sleeves, but also under the hood parts, e.g. throttle bodies, inlet tanks, water pump bodies (Vaidya, 2011). PPS have superior fire resistance, and is used where this is an important factor. Laminated composites that are based on PPS have poor resistance to transverse impact as a result of the poor adhesion of the fibres to the matrix (Chung, 2004). The material's resistance to heat, acids and alkalis is excellent, but also to prolonged combustion, mildew, bleaches, aging, sunlight and abrasion. Polyphelylene sulphide can be moulded, extruded or machined to high tolerances (Vaidya, 2011).

Polyamide (PA)

Polyamide, nylon, is used in a wide range of automotive parts, such as interior, gears, bearings, housings, air ducts etc. The temperature performance is excellent up to 200°C; the melting point is in the range 215-220°C. Polyamide is a good electrical insulator when the material is dry, but the material tends to absorb moisture from the air, which affects the mechanical and electrical properties (Vaidya, 2011).

A.1.3 Sandwich-structured composites

Sandwich-structured composites consist of a lightweight core separating two thin layers of composite or metal sheets (Drechsler, et al., 2009). The material is commonly used in automotive, truck and mass transit industry due to its superior bending stiffness (Vaidya, 2011). Balsa wood, polyvinyl chloride foam, polyurethane foam-filled honeycomb and polypropene honeycomb are all examples of cores used within heavy trucks, mass transit and bus floors. The sheets are usually made of thermoset E-glass/epoxy, E-glass/polyester and thermoplastic self-reinforced polypropene, E-glass/PE. If the thickness of the core is doubled, is the flexural stiffness increased seven times, with an increased weight of three per cent. Panels of sandwich material have become more common as a replacement for plywood and floor panels of truck trailers (Vaidya, 2011). Lamborghini uses sandwich composites in the car, Murcièlago, which is excellent for vibration damping (Feraboli & Masini, 2004).

A.2 Manufacturing methods

The process for manufacturing a vehicle with composite materials consists of four major steps, Figure 36. These steps are:

1. Production of fibres.
2. Preformed material in shape of prepregs or dry fibre performs are manufactured, this step is not necessary to do before manufacturing the composite, as matrix and fibres can be impregnated during the manufacturing.
3. Manufacturing of composite parts, here is the fibres reinforcing the matrix.
4. Parts are assembled to create a whole product. It is also in this step the parts are processed in different ways, e.g. surface treatment. More about this in section A.3 Processing.

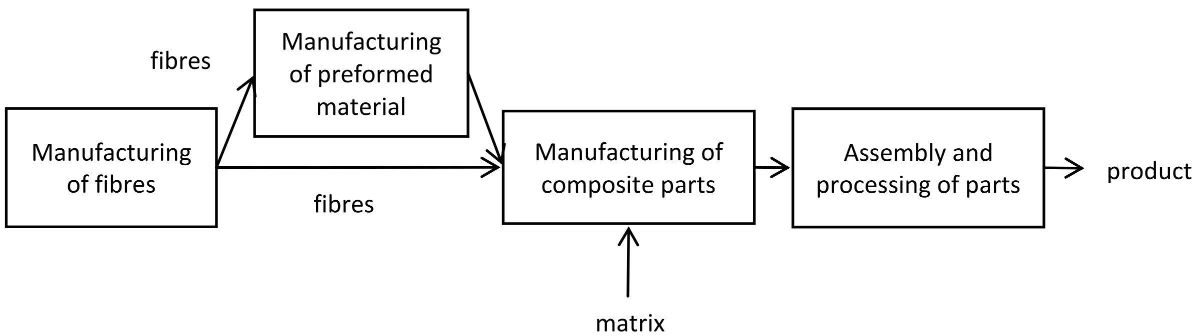

Figure 36. The manufacturing process

Manufacturing of preformed material and composites will be covered in this chapter. Assembly of parts and processing is covered in chapter A.3, Processing. The manufacturing of carbon fibres is briefly mentioned in A.1.1.1 Carbon fibres.

The manufacturing process can be divided into three major steps, Figure 37: placement of fibres, matrix application and curing. There are several methods used for manufacturing, but how many of the steps they include differ. This chapter has therefore been divided according those three stages, and each method is placed in the section that best describes the process, prepreg and dry fibre preforms is for example both methods for placing the fibres. In those cases the method is fitting in more than one category; it is placed in the first one that occurs in the process flow. It is often necessary to combine different methods in order to manufacture the composite, weaves of prepreg can for example be used in the RTM process where the matrix application and curing is done.

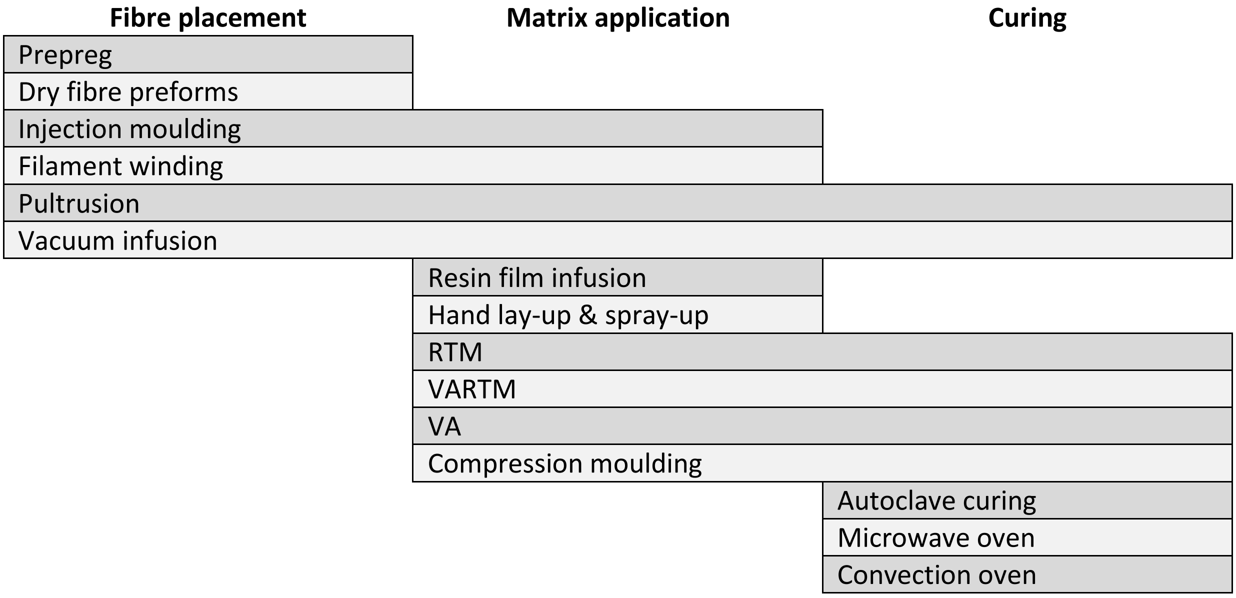

Figure 37. Manufacturing methods

The manufacturing methods can be categorised in other ways than described above, Drechsler et al. (2009) categorise the manufacturing in four general technologies, depending on how the production is done. These are for directionally oriented continuous fibre composites, mainly in thermoset resins:

1. The fibres are impregnated during placement on the tool. E.g. hand lay-up, filament winding, and pultrusion.
2. The fibres are impregnated and procuring to a semi-finished prepreg. The process is up to now the most important one for aerospace applications.
3. Dry fibre performs (e.g. weaves, knits or braids) are manufactured and in a second step impregnated with liquid resin. Because this manufacturing method allows high degree of automation is this especially interesting for high-volume applications.
4. Fibres are impregnated with a thermoplastic matrix and consolidated to semi-finished products. These semi-finished products are reheated and formed to the part geometry in a second step (Drechsler, et al., 2009).

Spray-up, press moulding and injection moulding mainly produce short fibres, and this leads to random fibre reinforcement (Drechsler, et al., 2009). The manufacturing is affected of both the reinforcement type and the matrix, and the manufacturing methods can be categorised according to this. Campbell (2010c) have divided the methods after the type of polymer matrix; thermoset or thermoplastic matrix, and after the fibre type; short or continuous, see Figure 38.

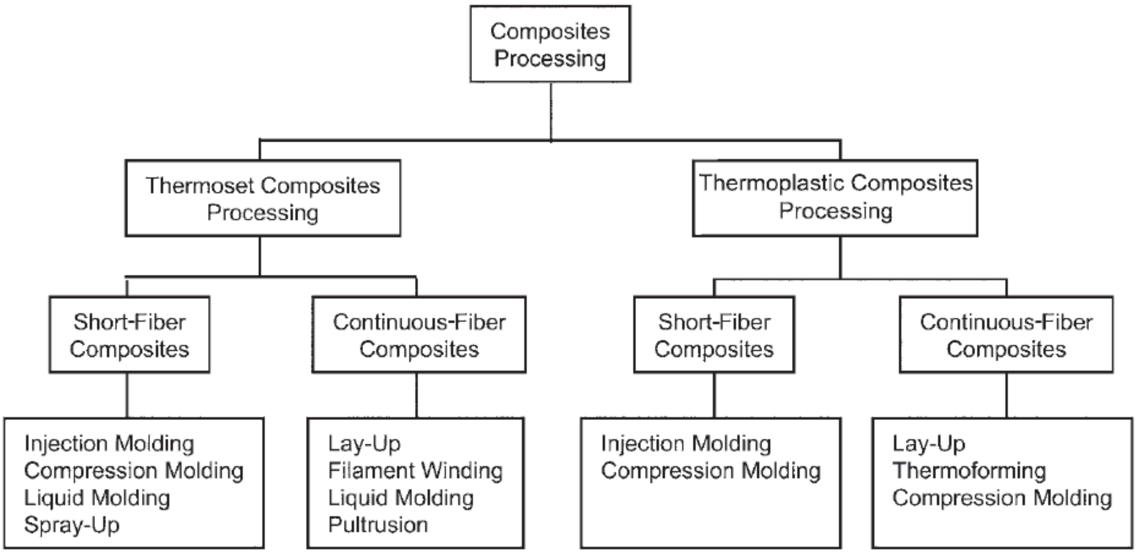

Figure 38. Manufacturing methods depending on polymer and type of fibre (Campbell, 2010c, p. 3)

There are several aspects that have to be considered when choosing the most appropriate manufacturing method (Hoebergen & Holmberg, 2001):

- The production volume, i.e. the number of parts
- The size and geometry of the part
- The required performance
- The surface finish required

The costs are also a factor that has to be considered as they can vary between the different methods. In Figure 39 can a comparison of costs for different methods compared. The more $-signs, the more expensive is the process (Hoebergen & Holmberg, 2001). Autoclave prepreg is according to this the most expensive process, but the costs differ between the processes, the workshop requirements is for example most expensive for hand lay-up and spray-up, while they have low equipment cost.

	Vacuum infusion	RTM	Hand lay-up	Spray-up	Low P/T prepreg(a)	Autoclave prepreg
Workshop requirements	$$	$$	$$$$	$$$$	$$$	$$$
Equipment	$$	$$$	$	$$	$$$	$$$$$
Tooling	$$	$$$$	$$	$$	$$	$$$
Ancillary materials	$$$	$$	$	$	$$$	$$$
Raw materials	$$	$$	$$	$	$$$	$$$$
Labor	$$	$	$$	$	$$$	$$$

(a) P/T, pressure/temperature

Figure 39. Comparison of costs for some manufacturing methods (Hoebergen & Holmberg, 2001, p. 503)

How the surface of the reinforcement is treated is necessary for improving the bounding between the fibres and the polymer matrix. The treatment involves oxidation treatments and the use of coupling agents, wetting agents and/or sizing. For carbon fibres is treatment necessary for both thermoplastics and thermosetting matrices (Chung, 2004) (Chung, 1994b). The processing temperature is usually higher for thermoplastics than for thermosetting resins, it is therefore important when thermoplastics are used that the treatment is stable at higher temperatures, about 300 to 400°C. One type of surface treatment is oxidation treatments; it can be applied by gaseous, solution electrochemical and plasma. The main purpose is to remove a weak surface layer from the fibres, some types of oxidation treatments roughen the fibre surface and in such way enhancing the mechanical interlocking between the fibres and the matrix. The oxidation treatments do not improve the fibre wetting (Chung, 1994b).

The most common way of producing fibre composites is by impregnation of the matrix or matrix precursor, in liquid state, into the fibre perform. The preform of the fibres is usually in form of woven fabric. The fibres and matrix can also be intermixed in the solid state by commingling reinforcing fibres and matrix fibres. This can be done in several ways, for example by coat the fibres with the matrix material or by sandwiching the fibres with foils of the matrix material. When the impregnation or intermixing is done is the material cured, often under heat and pressure (Chung, 2004).

A.2.1 Fibre placement

There are different methods for placing the fibres, they can for example be woven into weaves and pre-impregnated with matrix, so called prepregs that shall be combine with other manufacturing methods. Prepreg and dry fibre preforms are placing the fibres. Injection moulding and filament winding includes also the placement of matrix, and pultrusion consists of all three steps.

A.2.1.1 Prepreg

- High material costs
- Time consuming
- Manual processing
- Limited to two-dimensional fibre reinforcement
- Often combined with e.g. hand-lay up

Prepreg is a method for producing semi-finished products of pre-impregnated unidirectional fibres or weaves. They are soft and tacky at room temperature and the prepreg layers can then be placed onto a mould after cutting. After impregnation is the prepreg is cooled and stored at -18°C to stop the chemical reaction, to ensure that the material stays semi-finished/semi-cured (Drechsler, et al., 2009). As the prepreg is not fully cured it is possible to storage the prepreg until it is needed for a moulding or laminating operation (Gooch, 2007h). The prepreg is the basis for high-performance structures with the highest potential for weight savings. The main disadvantages with the method are: high material costs, time-consuming manual processing and limitation to two dimensional fibre reinforcement that makes the laminate recipient to impact damage that can lead to delamination (Drechsler, et al., 2009). The method can be combined with other processes, such as hand lay-up where the pre-impregnated fibres are used in the process (Gooch, 2007f). Sheet moulding compound, SMC is used for prepreg in sheet form, instead of prepreg (Gooch, 2011).

A.2.1.2 Dry fibre performs

- Pre-shaped preforms
- Can improve damage resistance
- Possible to ship, storage and drape
- Complex shapes
- Often better performance than for prepreg based structures

Dry fibre preforms are fibres that are bonded together for example by braiding, embroidery or stitching. These preforms are not impregnated with matrix until a later stage in the process, which gives the possibility to manufacture more complex parts. In many cases is the mechanical performance better for these performs than for prepreg-based structures. The most important custom-made textile product is non-crimp fabric (NCF), where up to nine carbon fibres can be placed upon each other without crimp (Drechsler, et al., 2009). By using dry textile performs it is possible to reduce composite part costs, and have an ability to improve damage resistance. As they are manufactured as dry fibre preforms and are held together without any polymer or matrix material it is possible to ship, storage, drape, and pressed into shaped moulds. The fibre preforms are often used within RTM (Campbell, 2010i).

Braiding, embroidery and stitching are all processes for manufacturing dry fibre preforms, all three processes allow manufacturing of very complex preforms. There are two types of braiding, Cartesian 3D braiding and round braiding; the preforms are complex, near net shape, with load-adapted fibre geometry. The productivity is low, and the cross section is limited. It is possible to create hollow structures and profiles by using braiding and to increase productivity and quality can the braiding be combined with a robot. When embroidery is used the reinforcement are stitched under computer control by a basic fabric with a thin fixing yarn. The third method, stitching, stitches set of basic textiles in order to create the preforms. The stitching yarn can have two functions, to hold the dry fibre preforms together to improve handling and the manufacturing process, or to improve the mechanical properties of the composite structure by realising three-dimensional fibre reinforcements. This method allows manufacturing of large, complex-shaped components as the stitching head only needs access to one side (Drechsler, et al., 2009).

A.2.1.3 Filament winding

- Fibre placement and application of matrix
- Cylindrical or spherical geometries
- Rocket motors, corrosion-resistant tanks, storage containers

Filament winding makes it possible to manufacture cylindrical or spherical geometries. The method is often used for manufacturing composite rocket motors, corrosion-resistant tanks and storage containers. During manufacturing with filament winding are bundles of fibres pulled through a resin bath and then winded onto a mandrel, see Figure 40. The mandrel is then cured in an oven (Chung, 2004). The most used fibres are glass, asbestos, jute, sisal, cotton and synthetic fibres. Polyester is a commonly used resin (Gooch, 2007e). The process is more automated, and the reproducibility and production rate is higher than for hand lay-up, but requires greater financial investments (Drechsler, et al., 2009) (Chung, 2004).

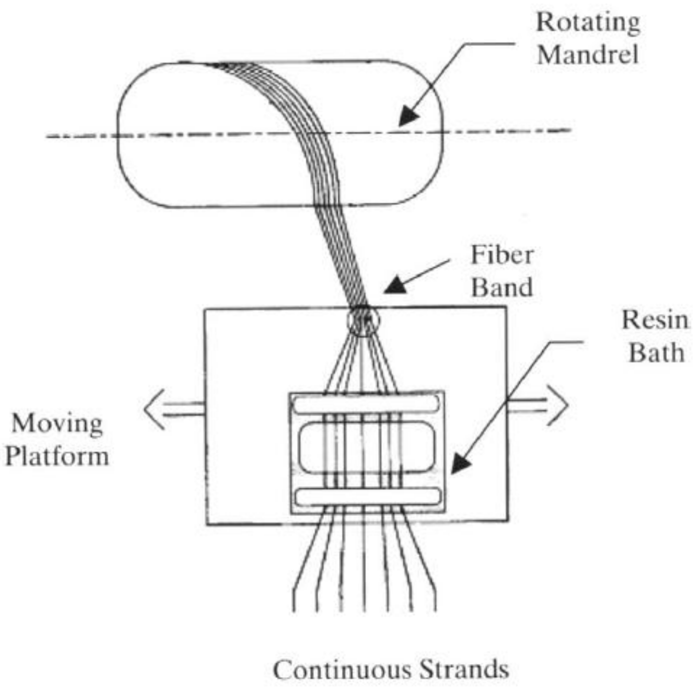

Figure 40. Filament winding (Campbell, 2004b, p. 22)

A.2.1.4 Pultrusion

- Fibre placement, matrix application and curing
- Solid and annular profiles
- Thermoset resins are often used, e.g. polyester and epoxy, but thermoplastic resins can be used
- Building sidings, fishing rods, golf-club shaft etc.
- Prepregs can be used

Pultrusion is a commonly used production method for producing continuous fibre sections of unidirectional reinforced polymers. The method is used for both producing solid and annular profiles. Resins of thermoset are often used, e.g. polyester and epoxy, but thermoplastic composites can also be pultruded. A schematic picture of the process can be seen in Figure 41. Dry fibre bundles are pulled together through a resin bath and then through a series of wipers to remove any excess resin. The fibres are pulled through a spider to separate them before they are passed into the die. The die is heated and by doing that is the resin cured (Chung, 2004). To improve the part quality it is possible to use prepregs. The main limitation of the method is that the cross-section cannot be changed (Drechsler, et al., 2009). Pultrusion is used for manufacturing building sidings, fishing rods, golf-club shafts etc. (Gooch, 2007h).

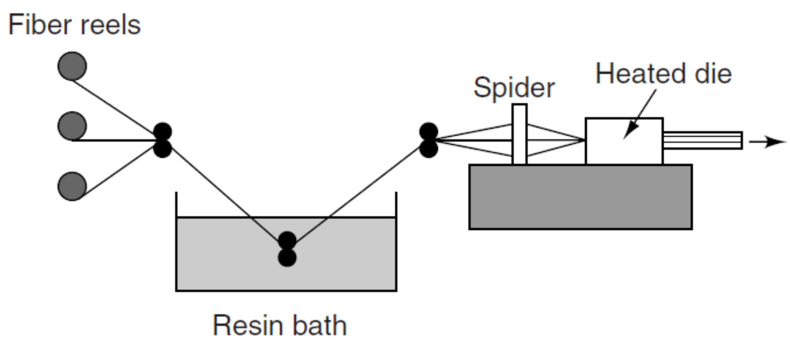

Figure 41. Principle of pultrusion (Chung, 2004, p. 36)

A.2.1.5 Vacuum infusion

- Placement of fibres, injection of matrix and curing
- Intermediate volumes of parts, about 1000 parts per year
- Small and large parts
- Complex parts
- Polyester and vinyl ester common resins

Vacuum infusion derivatives from RTM, resin transfer moulding, and has been developed as an alternative to hand lay-up and spray up techniques. The vacuum infusion process consists of a few steps; dry reinforcement is placed in the mould and the mould is closed. Resin flows through the mould and impregnates the reinforcement and is then cured. After curing is the mould opened and the product is removed. Vacuum infusion makes it possible to manufacture an intermediate volume of parts every year, up to about 1000 parts per year. Both small and large parts can be manufactured, with both high and low performance and there are no limitations in part geometry. Even if it is possible to manufacture large parts with vacuum infusion, the risk that something goes wrong is higher with large parts. The manufacturing of large parts is also related to practical problems, such as accessibility of the part. According to Hoebergen and Holmberg (2001) is the major advantage with vacuum infusion the absence of large forces on the mould, and the major disadvantage is the sensitivity of leakage. Polyester and vinyl ester are the most commonly used matrices for vacuum infusion, even if others such as epoxy and phenolic resin can be used. Most types of reinforcement used for RTM or lay-up processes can be used with vacuum infusion. It is also possible to apply different kind of cores and inserts, the cores must be made of a closed-cell material, but there is still a risk for void-rich areas. It is the combination of the used mould system and the resin/reinforcement that determine the surface finish of the part. High quality surface is normally easy to achieve on one of the sides. Net shape manufacturing is rare with vacuum infusion and it is therefore usually necessary to trim the edges (Hoebergen & Holmberg, 2001).

A.2.1.6 Injection moulding

- Both placement of fibres and matrix application, curing can be done
- Complex parts
- High volumes, more than a million parts per year
- Low cost per part if high volumes
- Expensive tooling
- Short fibres
- Mainly thermoplastic resins

Injection moulding is mainly used for composites with thermoplastic resins, and glass fibres are the most common fibres. Carbon fibres can be used when higher properties are required. With injection moulding it is possible to produce complex parts, with thermoplastic resins in high volumes, with more than a million parts per year. The cost per part can be quite low thanks to the high volumes. In order to perform injection moulding is special matched metal died needed, because of high processing temperature and pressure. As a result of this are the tools expensive. The moulding compound, in pellet form, is melted as it progresses down the screw by a combination of heat and shearing action. The material is then injected under high pressure into a relatively cold closed die. The mould is cooled down, and more moulding component is added because of shrinkage during cooling. When the part is cooled it is removed from the mould. A picture of the injection mould machine can be seen in Figure 42. It is possible to use injection moulding for thermosetting resins, but the material is not as compatible with the method as thermoplastics are. The temperature has to be much lower for thermoplastics, and the mould itself is heated (Campbell, 2004a).

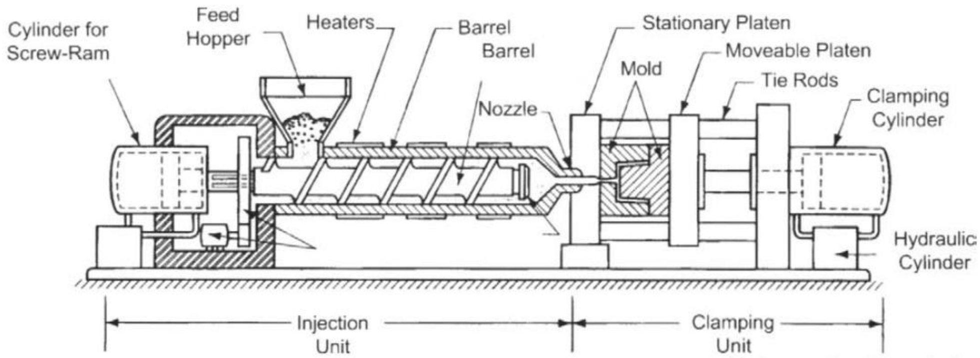

Figure 42. Injection moulding machine (Campbell, 2004a, p. 424)

A.2.2 Matrix application

This section describes how the matrix could be applied to the fibres. In some of the cases is the matrix application and curing done in the same process, and those methods are also described here. When curing is not included in the process, is usually another method used for curing.

To be able to consolidate the fibre layers or prepreg lay-up is good resin flow and compaction necessary to get component with good fibre wet-out and without defects such as voids, interply cracks, resin-rich areas or resin poor areas. However good resin flow is by itself not necessary for producing good consolidation. Both for the resin flow and compaction is application of pressure needed. This is done to remove trapped air or volatiles when the liquid flows through the fibre layers or prepreg lay-up, and to suppress voids and attain uniform fibre volume fraction. For thermoset resins can the curing can take place at the same time as the resin flow, but it is important that the resin flow is not rising too rapidly because of the curing, as risk is that the flow is inhibited and causes voids and poor interlaminar adhesion (Mallick, 2007c).

A.2.2.1 Liquid moulding

- Extremely complex and dimensionally accurate parts
- Possible to integrate several individual parts in one single moulded part
- Possible to have sandwich cores in the parts

It is possible to manufacture very complex and dimensionally accurate parts by using liquid moulding. One advantage with liquid moulding is that it is possible to make one single moulded part instead of several individual parts. It is also possible to integrate a sandwich core in the interior of a liquid moulded part (Campbell, 2010i). RTM, VARTM, VAP and RFI are different types of liquid moulding, and are described below.

A.2.2.1.1 Resin transfer moulding (RTM)

- Matrix application and curing
- Resin is injected into a matched mould under pressure
- Prepregs can be used
- Excellent surface finishes
- The costs for tooling may be high
- Thermoset, e.g. polyester vinyl ester and epoxy
- Possible to combine RTM with vacuum assistance
- Necessary with sufficient part quantities to justify the tooling cost

Resin transfer moulding, also called RTM, is well suited for fabricating three-dimensional structures where tight dimensional tolerances on several surfaces are required. A dry fibre preform is placed in a closed mould, impregnated with a resin under high pressure and cured in the mould. The curing can be done in several ways with matched die moulds, they can have integrated heaters, be placed in an oven, or be placed between a heated platen press that provides the heat and reaction pressure for the mould (Campbell, 2010i). The tooling is matched to the parts profile, and the initial investment is relatively high. To justify the cost of the tooling sufficient part quantities is necessary, usually in the range from 100 to 5000 (Campbell, 2010i). In order to reduce the void content in large parts can several injection points be used and vacuum applied before the injection (Drechsler, et al., 2009). The mechanical properties are similar to autoclave parts, with a void content less than one per cent. The cycle times can be very short, and the design flexibility is considerable, as reinforcement, lay-up sequence, core material and mixed material can be considered. The need for labour intensity and skill levels is low (Campbell, 2010i). Another advantage of RTM is the possibility to encapsulate metal inserts, stiffeners, washers etcetera within the moulded laminated (Mallick, 2007c). There are however disadvantages with the method: the mould and tool design critical to part quality, the software for mould filling is still in development stages and RTM requires matched leak-proof moulds (Campbell, 2010i). Thermoset matrices are used for RTM (Drechsler, et al., 2009). For high quality parts for electrical and aerospace applications is epoxy commonly used, while polyester and vinyl ester are used for consumer products such as pipes, pressures vessels and in automotive industry (Chung, 2004).

A.2.2.1.2 Vacuum assisted RTM (VARTM)

- Both application of matrix and curing
- Prepreg and preforms can be used
- Large components
- Less expensive tooling than for RTM
- Not as good tolerances as for RTM
- Single side components used
- Excellent surface finish on the tool side

VARTM makes it possible to manufacture large-scale composite parts for commercial and military applications. The method was developed to replace hand lay-up and to reduce cost, minimise styrene emission and on the same time maintaining simple single-sided mould systems (Li, et al., 2004). The tooling for VARTM is less expensive and simpler to design than for RTM processes as the process only uses vacuum pressure for both injection and cure (Campbell, 2010i). The VARTM-process consists of a single sided tool with a vacuum bag, Figure 43. Normally do integrally heated tools or ovens provide heat, and as the pressure is low can low-cost, lightweight tools be used. It is possible to incorporate lightweight foam cores into the lay-up due to the lower pressure in VARTM processes. The viscosity of the resin needs to be lower compared to RTM as the resin is injected in the preform only by vacuum pressure. VARTM is used to build fibreglass boat hulls, and in the aerospace industry. However, the dimension tolerances cannot be as tight as for RTM, neither will the surface finish on the bag-side be as good as the surface of a hard-tooled mould. The thickness of the part is usually a function of the lay-up of the preform, how many plies that are used and the quality of the vacuum. The quality of the vacuum is also affecting the performance of the composite (Campbell, 2010i).

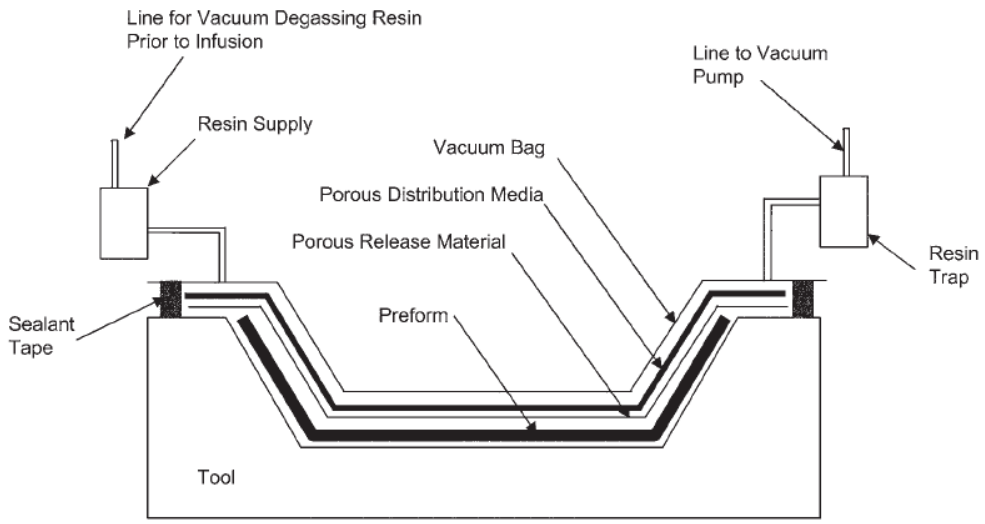

Figure 43. The VARTM process (Campbell, 2010i, p. 174)

A.2.2.1.3 Vacuum-assisted process (VAP)

- Matrix application and curing
- Improvement of VARTM process
- High-quality products
- Good process control
- Thermoset resin is used

Vacuum-assisted process, VAP, is designed to improve the characteristics of the VARTM process. In VAP is a membrane added to the VARTM process, which is permeable to gas but the resin is not let through at the same pressure. As the resin cannot pass through the membrane is uniform vacuum on the surface achieved. Thanks to the membrane let through the gas can the process be degassing during the whole process, due to this is the need of changing the vacuum bag to keep an excellent vacuum eliminated. The vent is also moved, compared to VARTM to avoid the risk of leaking resin. Using VAP can decrease the void content and the thickness gradient. Temperatures up to 200°C can be applied to the VAP process (Li, et al., 2004). VAP gives high-quality products and good process control (Drechsler, et al., 2009), and the void content and thickness gradient can be decreased (Li, et al., 2004). In similarity to VARTM is thermosetting resins are used (Drechsler, et al., 2009). The process is for example used for producing the Visby class corvettes, warships which are totally made in carbon fibre composites (Kockums AB, n.d.).

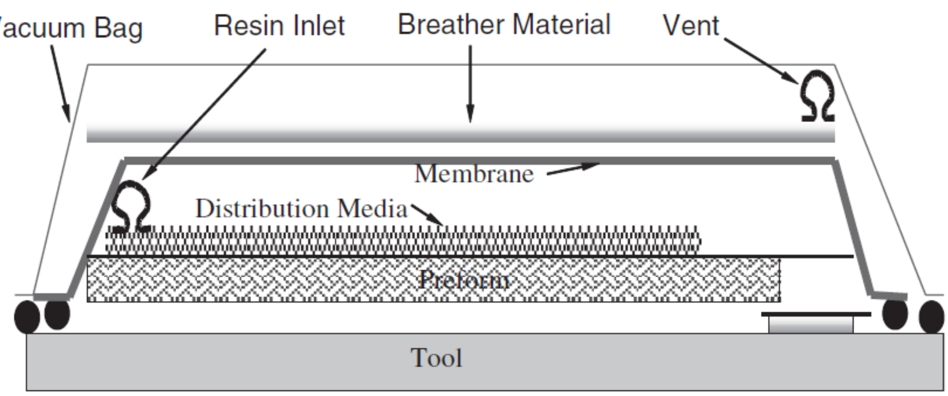

Figure 44. The VAP process (Li, et al., 2004, p. 1805)

A.2.2.1.4 Resin film infusion (RFI)

- Application of matrix and curing
- Stitched preforms can be used
- Resin films are used instead of liquid resin
- Possible to manufacture complex parts
- High quality parts possible to achieve

Resin film infusion, RFI, was originally developed by NASA, and uses a film of resin instead of liquid resin. This film is placed in the bottom of the tool and a stitched preform is placed on top of it. Under autoclave heat and pressure is the film melted and forced into the preform. When the resin has melted and forced into the preform is the temperature raised and the part cured. It is possible to manufacture complex parts with the method, but matched dies are normally needed. The production of high quality parts is also depending on the tooling. In order to produce these high quality parts it is necessary to understand the compaction and permeability of the preform and the viscosity and kinetics of the resin system. There are different variants of RFI, for example could individual resin layers be placed between the preform layers (Campbell, 2010i).

A.2.2.2 Compression moulding

- Matrix application and curing
- Prepreg is used
- Small to intermediate sized parts with high quality
- Relatively high rates
- Inexpensive

It is possible to manufacture small and intermediate-sized parts with high quality at relatively high rates with compression moulding. The method is relatively inexpensive, in spite of cost involved in the production and maintenance of the mould. Two moulds are used to manufacture composite parts with compression moulding. The wished number of pre-impregnated layers of composite is placed on the lower mould. The upper mould is lowered until the required pressure is achieved, and the composite has contact with the both moulds. Then is the composite heated until the material is cured and solidified. Certain polymers e.g. epoxy resins, flows during processing (Chung, 2004) (Gooch, 2007c). It is important to manufacture the moulds with great care to receive surfaces with high quality of the composite. The surfaces of the moulds need to be replaced after continued use in order to maintain the desired surfaces (Chung, 2004). A schematic of the process can be found in Figure 45.

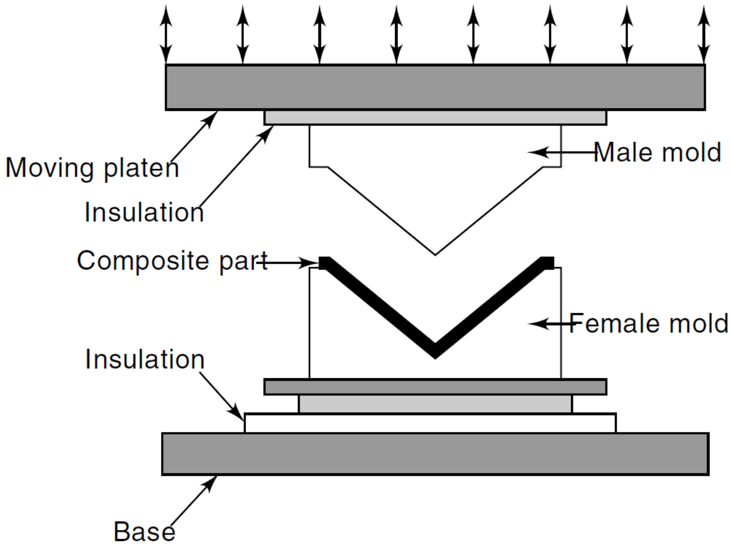

Figure 45. Principle of compression moulding (Chung, 2004, p. 35)

A.2.2.3 Hand and spray lay-up

- Matrix application and curing
- To get higher properties on the parts can the lay-up be combined with other processes e.g. autoclave curing
- Large parts, small volumes, e.g. glider and yacht manufacturing
- Thermoset and thermoplastic
- Long production cycles

Hand lay-up, also called hand lamination, is the easiest way to manufacture composite parts, and the method is used for large components in small volumes; primary for glider and yacht manufacturing. The tooling is simple but requires good manual skills to reach quality (Drechsler, et al., 2009) and the manufacturing cycles are relatively long (Chung, 2004). The fibres are usually used in form of a weave (Drechsler, et al., 2009), which, impregnated with resin or not, is placed on a mould or over a form. The reinforcement is impregnated and/or coated with fluid resin. After this the resin is cured, followed of the extraction of the cured article from the mould (Gooch, 2007f). See Figure 46 for the principle of the process. Hand lay-up is normally performed at room temperature, but the parts are sometimes tempered in a second step to improve thermal stability. The void content is relatively high as no vacuum assistance or consolidation pressure is used (Drechsler, et al., 2009). Hand lay-up is sometimes called contact-pressure moulding, when little or no pressure is used in the curing process, but when pressure is applied is the process instead named by the method of the applying pressure, e.g. vacuum-bag moulding or autoclave moulding (Gooch, 2007g). Composites based on polyester are generally manufactured using hand lay-up or spray-up techniques (Chung, 2004). For hand lay-up is continuous fibres used, the similar process spray-up is used for composites with short fibres. The latter includes spraying short fibres mixed with a catalysed resin onto the mould. The glass resin mixture is then consolidated by manually rolling the surface (Chung, 2004).

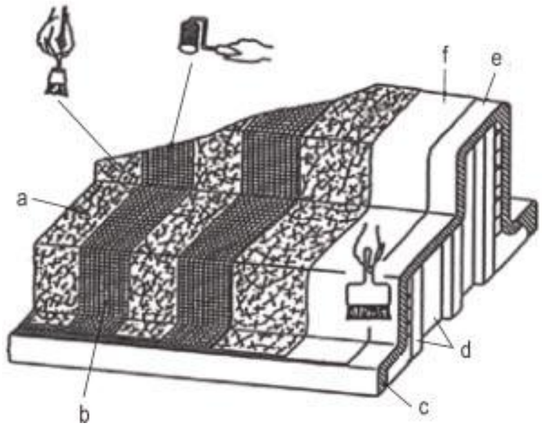

Figure 46. The principle of hand lay-up (Drechsler, et al., 2009, p. 4)

A.2.2.4 Bag moulding

- Possible to combine with lay-up processes, to get higher mechanical properties compared to lay-up
- Large components, e.g. aerospace

Bag moulding can be used to reduce voids and porosity in composite material if higher mechanical properties are needed to the material compiled from hand lay-up, (Campbell, 2004a). There are three types of moulding: autoclave moulding, vacuum bag moulding and pressure bag moulding (Chung, 2004). To uniformly apply pressure over one surface of the laminate is a flexible bag or mattress used. A preform including a sheet of pre-impregnated fibres is placed over or in a rigid mould to form one surface of the part. The bag is then applied to the upper surface, after this is the pressure applied, by vacuum, in an autoclave, in a press or by inflating the bag. Steam can be used to apply heat in the autoclave. Sometimes is the process called autoclave moulding when an autoclave is used (Gooch, 2007b). It is possible to manufacture large composite parts for e.g. the aerospace industry with bag moulding (Chung, 2004).

A.2.2.4.1 Vacuum bag moulding

When vacuum bag moulding is used is a flexible film placed over the complete lay-up or spray-up, the joints is sealed and a vacuum drawn. The pressure from vacuum bag helps to minimise voids in the laminate and forces excess resin and air from the lay-up. Usually is glass fibres used for lay-up techniques, and the pressure yields higher glass concentrations and provides better adhesion between layers in a sandwich construction (Campbell, 2004a).

A.2.2.4.2 Process bag moulding

A tailored rubber sheet is placed against the finished lay-up or spray-up, and air-pressure is applied between the rubber sheet and a pressure place. To help the resin to cure faster can steam be applied (Campbell, 2010i).

A.2.2.4.3 Autoclave moulding

- Large, high quality components
- Small volumes

- Relatively expensive
- Long processing cycles
- Prepreg is used
- Thermoset and thermoplastic resins

Autoclave moulding more automated than hand lay up (Drechsler, et al., 2009) and is suitable for manufacturing of large, high quality components. It is most commonly used for manufacturing of limited high quality components, such as parts for the aerospace industry. It is a relatively expensive process, with long processing cycles (Chung, 2004). An autoclave, mould, pressure source and a vacuum pump are needed for the manufacturing. Prepreg is cut into the right shape and placed in the mould. The bleeder/breather system is prepared and the material bagged. This is followed by the curing cycle and the part can be removed. A cross-section of autoclave moulding can be seen in Figure 47. Thermoset, epoxy, polyester, polyimide, and thermoplastic resins, PEEK, can be used, in combination with resins such as carbon, Kevlar and glass fibres and fabrics (Daniel, 2006).

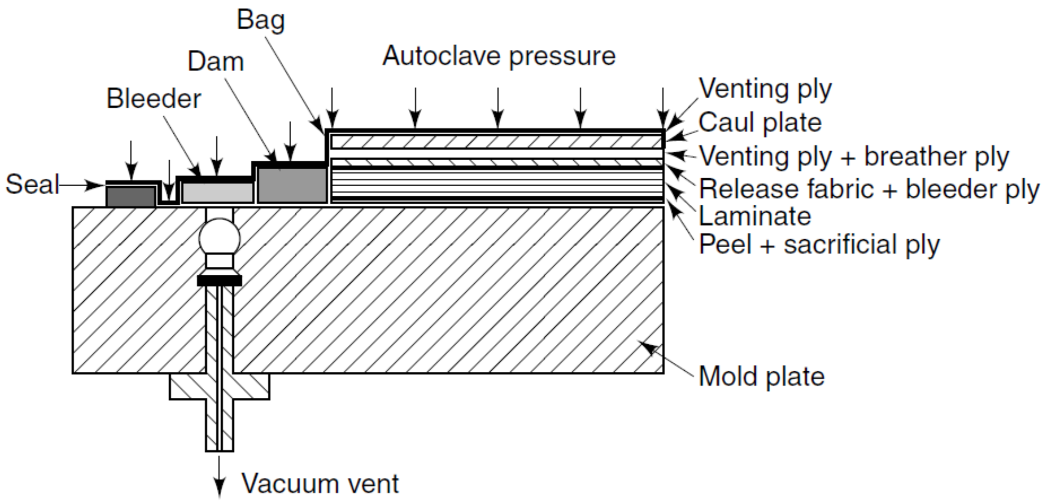

Figure 47. The principle of autoclave moulding (Chung, 2004, p. 34)

A.2.3 Curing

Curing is the last step in the manufacturing process of composite parts. The matrix is cured, often by application of heat, e.g. in an autoclave, a convection oven or in a microwave oven. Autoclaves are commonly used for e.g. prepreg and hand lay-up, while for filament winding is ovens more common (Campbell, 2010i). During the curing are heat and pressure applied under a predefined length of time. High temperatures are required to initiate and maintain the chemical reaction needed to transforms the material into a fully cured solid. The pressure is applied to ensure the force needed for the flow of resin into the material, and to consolidate the unbounded plies into one laminate. The time needed to cure the material is called curing cycle. Other factors except time, temperature and pressure is affecting the curing process, such as resin chemistry, and if any inhibitors or accelerators are present (Mallick, 2007c). Thermoset resins harden gradually under temperature and pressure (Chung, 2004).

A.2.3.1 Autoclave

One way to cure composite parts is by using an autoclave. This is the most commonly used method for producing laminates with high quality to the aerospace industry (Campbell, 2010i). An autoclave is a cylindrical pressure vessel that is capable to generate pressure up to several atmospheres. It is heated by a series of electrical heaters (Chung, 2004). The principle of autoclaves is differential gas pressure. To remove the air from the component is a vacuum bag evacuated and the autoclave applies gas pressure to the part (Campbell, 2010i). An inert gas, e.g. nitrogen or carbon dioxide, is normally used to create the pressure in the autoclave. Air can be used but the risk for fire within the autoclave during heated curing cycle increases (Campbell, 2010g). The autoclave can be used for many different types of structures, and thanks to that gas pressure is applied isostatically can any shape be cured. It is also possible to manufacture either a single large part or several smaller parts loaded onto racks and cured as a batch. The limitation is the size of the autoclave and the tool is very expensive (Campbell, 2010i). When curing a composite in an autoclave is the heat up rate a concern, as if the rate is too fast can the laminate be degraded because of a significant rise of temperature in thick laminates. For epoxy is this rare, mainly because thick laminates are heated up slowly and thick laminate parts are often matched in metal tools (Campbell, 2010g).

A.2.3.2 Ovens and presses

Ovens and presses can also be used to cure composite structures. Ovens are commonly heated with convective forced air; the process can be used to cure composite flow and allow volatiles to escape. The void content in oven-cured composites is usually much higher than for parts cured in an autoclave as the pressure in the ovens are only provided by a vacuum bag. In a heated platen press can much higher pressure be applied and be used to consolidate the plies and reduce the risk for void formation and growth. When using presses it is on the other hand necessary to have matched metal tools for each part configuration, and the number of part that can be processed at the same time is limited (Campbell, 2010i).

A.3 Processing

This section describes different ways of processing the CFRP after the manufacturing process, in order to give it its final shape and to prepare it for the assembly. The chapter is divided in four subsections: machining/moulding, joining, and surface treatment. The first section includes how the composite is machined to meet tolerances and its final shape. Joining is about different types of joining, and how the composite parts can be joined together.

A.3.1 Machining

Machining is usually carried out after the production to give CFRP parts their final shape and assembly requirements, and to meet required surfaces and to manufacture fitting and joining surfaces. Machining can broadly be divided into two categories, conventional/classic and non-traditional machining. The opinions of which is the most common machining methods differs between the literatures, Hintze, Hartmann and Schütte (2011) say that classical machining methods, e.g. milling and drilling mainly is used. In their article mention Sheikh-Ahmad, Urban and Cheraghi (2012) turning, sawing and grinding as processes for machining. Campbell (2010d) on the other hand mean that conventional machining methods, such as milling is not normally used for composites because they cut through the continuous fibres and reduce the strength of the composite. The mechanical strength of the composites can be reduced due to these machining methods (Sheikh-Ahmad, et al., 2012). Water jet machining, laser cutting and EDM is together categorised as non-traditional machining methods, where water jet machining is the most common. According to Sheikh-Ahmad (2009b) have non-traditional machining many advantages over traditional machining. The production rates are higher, greater flexibility, and capability to produce complex contours and shapes. No cutting tools are needed and the needed fixture is at a minimum, if any. These methods are relatively new, and development is therefore is development needed in order to learn more about how they could be used for machining FRC (Sheikh-Ahmad, 2009b).

Fibre reinforced composites are produced near net shape and therefore is the need for roughing operations low. Lighter cutting forces can thanks to this be applied to the tool, which helps to reduce chipping. The main focus is therefore on the machine tool and its structure. Much higher spindle speeds and higher feed rates than for metal cutting is needed due to the demand for higher productivity of FRP (Sheikh-Ahmad, 2009c).

The process of machining fibre reinforced polymers is challenging, from the point of cutting tool requirements. Cutting of FRPs takes place by compression shearing and fracture of the fibre reinforcement and matrix, this unlike metal cutting where plastic deformation is the predominant cause of chip formation. When cutting FRPs it is therefore is often sharp edges and large positive rake angles necessary to facilitate the shaving of the fibres, the material in the tool need to have high hardness and toughness to resist the fibres abrasiveness and the intermittent loads generated by their fracture. The numbers of material that can meet these requirements are limited (Sheikh-Ahmad, 2009c). For carbon fibres that are very abrasive and easily wear out conventional steel cutting blades, should trimming operators use either diamond coated circular saw blades, carbide router bits or diamond coated router bits (Campbell, 2010d).

A.3.1.1 Drilling

One of the most important machining processes carried out for composites are drilling. Drilling, counter boring, and countersinking are often necessary to use in order to prepare the parts for joining and assembly. Even if drilling is very important it is one of the most challenging machine operations. Thermal management, tool wear, and delamination are key issues that have to be considered. Matrix and fibres have poor thermal conductivity and therefore is heat built up at the cutting area when drilling. Most of the heat has to be conducted away through the tool. As the generated heat is affected by the cutting speed and the feed rate it is only possible to machine FRPs in a limited range process in order to avoid heat damage. To avoid this problem can in some cases coolant be used. It can be difficult to attain dimensional accuracy of the drilled holes due to different thermal expansion coefficients between fibre and matrix. The holes can also sink after drilling and cause poor assembly tolerance. Tool wear is another difficulty, and reinforcement fibres cause severe wear on the tools by abrasion of the cutting edges. In turn wear of the cutting edge increases the thrust force, which is the most controlling factor of the onset delamination (Sheikh-Ahmad, 2009a).

A.3.1.2 Milling

According to Sheikh-Ahmad (2009a) is milling is another frequently used processes for material removal when manufacturing parts in FRPs. Campbell (2010d) on the other hand means that milling is not that common when processing composites as the method cut through the continuous fibres and reduces the strength. Compared to milling of metals is much less material removed when milling composites, this because FRPs usually is made near net shape, why milling mainly is used for deburring and trimming the composite. It is common for milling that more than one cutting edge is used (Sheikh-Ahmad, 2009a).

A.3.1.3 Turning

Turning can finish parts that are axisymmetric. These parts could be axles, columns, bearings or rolls. Turning is similar to milling, but instead of a moving tool is the part moving. Turning has become an important process for finish machining of high accuracy components and highly precise joint areas, due to more advanced technologies for filament winding. The more advanced technologies for filament winding have increased the use of axisymmetric parts in construction, industrial and transportation applications. To successfully implement turning it is necessary to proper understand the composite behaviour during processing. For turning is machinability studied in terms of tool wear, cutting forces, cutting temperatures and surface quality. The type of fibre, their orientation and volume fraction are material properties that significantly influence machinability (Sheikh-Ahmad, 2009a).

A.3.1.4 Abrasive machining and grinding

Abrasive machining and grinding are both methods for removal of material by the motion of small, hard particles that are attached to a relatively rigid body. Grinding is a major manufacturing process, and abrasive machining is a relative new process. The difference between the two methods is mainly in the process parameters, depth of cut, wheel or cutter diameter, and work piece feed rates. Instead of machining with an edge defined cutter is abrasive machining used in edge trimming and bulk machining. The main reason for this is because delamination is almost completely eliminated and the surface is improved (Sheikh-Ahmad, 2009a).

A.3.1.4.1 Abrasive water jet machining

Abrasive water jet has become the preferred method for trimming cured composites (Campbell, 2010d). A high-speed water jet is used to accelerate abrasive particles at extremely high speeds so that the work piece material will erode and material be removed. With water jet it is possible to cut all materials without any particular heat damage or distortion, and it is one of the most environmental friendly material removal processes (Sheikh-Ahmad, 2009b). Water jet cutting give with delamination-free edges, and as no heat is generated under the process is the risk for matrix degradation eliminated. The tools are large and very expensive (Campbell, 2010d).

A.3.1.4.2 Laser machining

Laser machining is a thermal process where material is removed by melting and vaporisation. A laser beam is affecting the surface of the material, the heat is absorbed of the surface and is subsequently conducted deeper into the material. The heated material will melt or evaporate, depending on the material’s thermal properties and the induction time. The melted material is subsequently removed with the help of a subsequent gas. Different fibre reinforced composites have different thermal properties and the result of laser machining will be different. CFRP is the most difficult material to cut, because high thermal conductivity and high vaporisation temperature (Sheikh-Ahmad, 2009b).

A.3.1.4.3 Electrical discharge machining (EDM)

Electric discharge machining, EDM is also a thermal machining process that removes material by using spark erosion. The method is only suitable for material removal of electrically conductive materials, such as CFRP or carbon/carbon composites, and cannot be used to remove bulk material. EDM enables manufacturing with very tight tolerances and machining complex shaped cavities and holes with very small diameters. Delamination occurs with EDM, and is common at places where the fibres are perpendicular to the machining surface. It occurs mainly because of high temperatures and pressures associated with spark erosion, and due to mismatch between fibres and reinforcement (Sheikh-Ahmad, 2009b).

A.3.2 Joining

This section describes different techniques for joining CFRP. The purpose of structural joints is to transfer loadings from one side of the joint to the other (Matthews, 2001) through fastener elements. The holes for the bolts causes stress concentration in the composite joint plates; this can reduce the mechanical strength and fatigue life of the structure (Nassar & Yang, 2013). There are three main types of joints for polymer composite materials; mechanical fasteners, adhesives and welding. Thermoset matrices are commonly bonded by adhesive bonding, while welding usually is used for thermoplastic composites (Weber, 2010). Vaidya (2011) divides the joining methods into the same three categories as Weber; the categorising with specific methods can be seen in Figure 48. The joint is often seen as the weakest link that significantly can affect the reliability and safety of many mechanical systems (Nassar & Yang, 2013).

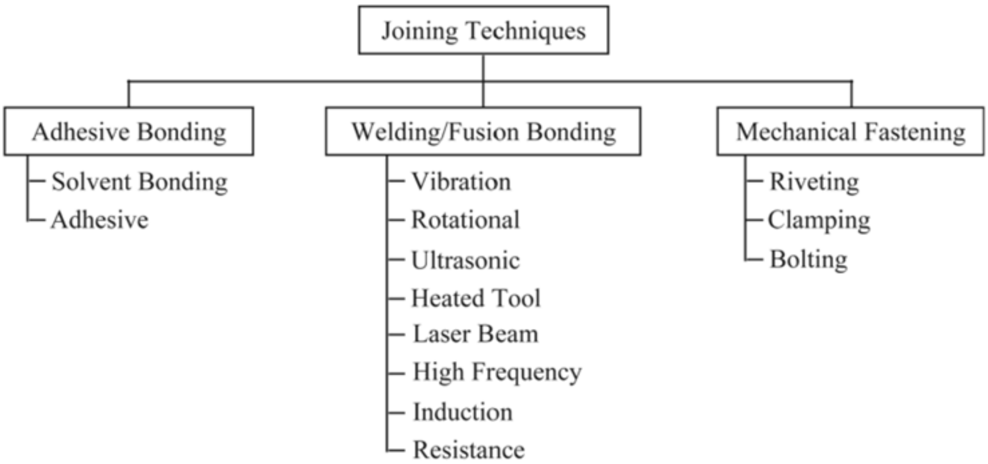

Figure 48. Joining techniques (Vaidya, 2011, p. 348)

A.3.2.1 Mechanical fastening

Mechanical fastening is for example used within the aircraft industry and ships, when adhesive bonding or welding is difficult or when the durability of bonding is questionable. Mechanical fasteners are also excellent when reassembly might be needed. Common fasteners are screws, rivets and bolts. Screws are only used for the most lightly loaded joints, rivets can be used if the laminate is not thicker than 6 millimetres, and bolts give the strongest joint. In order to be able to use joints it is necessary to drill holes in the laminate. These holes will raise the stress concentrations, reduce the strength (Matthews, 2001) and can cause structural instability (Nassar & Yang, 2013). Fasteners are also adding extra weight to the product. Drilling the holes requires diamond or carbide tripped bits and controlled feed rates to avoid delamination. When using mechanical fastening is the material combination in the composite very important, carbon fibres in an epoxy resin gives the strongest joint, followed by glass fibre and epoxy resin. Kevlar and epoxy gives the weakest joint. The thickness of the material can affect the performance of the joint, as well as other factors such as dimensions of the fasteners, distance from the centre of the hole to the end of the joint (Matthews, 2001). Some problems related to mechanical fastening (Vaidya, 2011):

- Stress concentrations created by the holes and cut-outs

- Delaminations from localised wear and drilling operations
- Mismatch of thermal expansion
- Water intrusion
- Electrical continuity
- Galvanic corrosion
- Additional weight
- Labour requirements

Even if mechanical fastening have several disadvantages can the method still be viable and a proven option (Nassar & Yang, 2013). In comparison to adhesive bonding is mechanical fastening a much more straight forward and the process is less risky, mechanical fastening requires less preparation and is not as affected by the environment. Depending on the type of fasteners can the composite be reassembled while necessary and mechanical fasteners are easier to repair on field than adhesive bonding (Campbell, 2010h).

A.3.2.2 Adhesive bonding

Adhesive bonding, also called gluing, is used to join laminates of CFRP together. A layer of adhesive is placed between the cured laminates in the area that should be joined together and are allowed to cure. The matrix resin acts as the glue and is cured so that the parts are joined together (Matthews, 2001). The mechanical performance in the structure is enhanced with adhesive bonding and the weight of the structure can be reduced, for the same performance as other approaches. The packing space required to achieve the mechanical performance target can also be reduced (Vaidya, 2011). Compared to mechanically fastened joints, offers adhesive bonding a much more efficient load transfer, but the requirements for technical and quality control are much stricter (Campbell, 2010h). By using adhesive bonding can the potential for stress concentration within the joints be minimised, this cannot be achieved with mechanical fasteners (Nassar & Yang, 2013).

The laminates are based on thermoset matrices and can be either cured or procured before joining (Matthews, 2001). Before joining the parts together it is important to prepare the surface by removing all traces of mould release agent and other contaminants from the composite. If the composite is joined with a metal, the metal need pre-treatment to remove any grease and any oxide layer. Epoxy is normally used as adhesive but other materials such as acryl or phenolic could be used (Matthews, 2001). If the strength of the joint is lower than for the rest of the composite will the damage tolerance be low and the joint can be the weakest link. If it is a thicker structure can the joint be made stronger by using enough steps in a stepped-lap joint (Campbell, 2010h). The performance specifications can be different in different areas of the vehicle and can be changed depending on the selected type of adhesive. It is possible, but can be expensive to use thermoplastics for adhesive bonding due to the surface preparation time, curing time and the chemicals needed (Nassar & Yang, 2013).

Adhesive bonding has generally been avoided in primary structures, due to lack of reliable, economical and feasible inspection methods, and because the requirements of tight dimensional tolerances in manufacturing (Nassar & Yang, 2013). Mangino et al. (2007) mean that adhesive bonding is the most promising technology for composites in the automotive industry, and there is a clear shift towards integral attachments that either are designed-in, like snap-fits, or formed-into the parts to be joined, e.g. hook-and-loop attachments. They also say that the technology for adhesive bonding is likely to be improved, but there is a need for new rules and numerical methodologies for the design, testing and process simulation of joints whichever technology will be used (Mangino, et al., 2007).

A.3.2.3 Welding

Welding is mainly used for thermoplastic composite joints (Vaidya, 2011). Thermoplastics are difficult to bond because of their low surface energy, but with appropriate pre-treatment can bond strengths similar to those obtained from thermosetting matrices be achieved. The characteristics of welded joints are similar to those of bonding joints (Matthews, 2001). Different types of welding are:

- Fusion bonding
- Thermal welding; not suitable for mass production
- Friction welding
- Electromagnetic welding

Thermoplastic matrices are not within the main focus of this project and welding will therefore not be considered any further.

A.3.3 Surface treatment

The focus on this project is the use of composite material in the bus chassis, and therefore is this chapter not very important, as the need for a high quality surface is not as high as for more visible parts such as a cabin. Two types of surface treatment will be described in this section: sealing and painting.

A.3.3.1 Sealing

Sealing is used to protect the component from corrosion, keep water out of the structure or to keep fuel in the structure. A thin layer of glass cloth can be placed on the surface of carbon/epoxy composites and aluminium joints. The cloth acts as an electrical isolator barrier and prevents galvanic corrosion on the aluminium. The sealer has to have good adhesion properties, high elongation, and good resistance to both temperature and chemicals. The sealer is usually accomplished by a polysulfide sealant that can resist temperatures up to 180°C for shorter time periods, if higher temperature resistance is needed is usually silicone sealants used as it can withstand temperature up to 260°C. It is important to choose a sealant with the right working life, as if it is too short the sealant may set before the job is completed, and if it is too long the curing time can take so long that the manufacturing schedule is affected (Campbell, 2010d).

A.3.3.2 Painting

Painting is according to Campbell (2010d) easier for composite material than it is for metallic structures. The most important thing is that the surface is clean, and if the part contains a peel ply it has to be removed. The surface is then prepared by scruff sanding, or by lightly grit blasting, and has to be primed within 36 hours after the sanding. If an aerospace application should be painted is the standard finishing system an epoxy followed by a polyurethane topcoat. When the primer and the topcoat are applied has the part to be cured for a minimum of six hours (Campbell, 2010d).

For many cars, e.g. Lamborghini Murcièlago is the requirements on the surface quite restrictive, as the fibre weave should not be seen through the paint. In order to receive this quality has the component to pass through several steps, for example is special epoxy resin used and the mould is prepared in different ways before the moulding; wax is applied and the mould is post-cured before polishing and application of releasing agent. Prepreg is used, and before applying it is a release agent applied and cured, followed by application of epoxy primer. When the moulding is done is the part sanded in order to get better adhesion to the paint. Then is the paint applied (Feraboli & Masini, 2004).

B Weight of specimens before and after environmental exposure

Specimen weight not rounded off, weights in grams

Static bending

Reference	B1	B2	B3	B4	B5	B6	B7	*Average*
weight before								
weight after								
VDA	B8	B9	B10	B11	B12	B13	B14	
weight before	2.6019	2.6058	2.6063	2.6011	2.5973	2.6079	2.5995	2.60
weight after	2.6142	2.6148	2.6172	2.6152	2.6070	2.6192	2.6095	2.61
increase in gram	0.0123	0.0090	0.0109	0.0141	0.0097	0.0113	0.0100	0.01
increase in per cent	*0.47%*	*0.34%*	*0.42%*	*0.54%*	*0.37%*	*0.43%*	*0.38%*	*0.42%*
Hydrothermal	B15	B16	B17	B18	B19	B20	B21	
weight before	2.5968	2.5948	2.4901	2.5316	2.5525	2.5653	2.5752	2.56
weight after	2.6037	2.6023	2.4975	2.5382	2.5605	2.5734	2.5844	2.57
increase in gram	0.0069	0.0075	0.0074	0.0066	0.0080	0.0081	0.0092	0.01
increase in per cent	*0.27%*	*0.29%*	*0.30%*	*0.26%*	*0.31%*	*0.31%*	*0.36%*	*0.30%*
Hydrothermal + salt	B22	B23	B24	B25	B26	B27	B28	
weight before	2.5789	2.5792	2.5927	2.5905	2.5876	2.5989	2.5934	2.59
weight after	2.5903	2.5922	2.6034	2.6015	2.5975	2.6098	2.6056	2.60
increase in gram	0.0114	0.0130	0.0107	0.0110	0.0099	0.0109	0.0122	0.01
increase in per cent	*0.44%*	*0.50%*	*0.41%*	*0.42%*	*0.38%*	*0.42%*	*0.47%*	*0.44%*

Average weight before [g]	2.583205
Total [g]	54.2473
Average weight after [g]	2.59321
Total weight after [g]	54.4574
Average increase [%]	0.39%

average VDA	0.40%
average hydrothermal	0.27%
average hydrothermal + salt	0.39%

Specimen weight not rounded off, weights in grams

Tensile test

Reference	D1	D2	D3	D4	D5	*Average*
weight before						
weight after						
VDA	D6	D7	D8	D9	D10	
weight before	21.3317	21.3605	21.4087	21.4029	21.3008	21.36
weight after	21.4113	21.4285	21.4931	21.4812	21.3897	21.44
increase in gram	0.0796	0.0680	0.0844	0.0783	0.0889	0.08
increase in per cent	0.37%	0.32%	0.39%	0.36%	0.42%	0.37%
Hydrothermal	D13	D14	D15	D16	D17	
weight before	20.6653	21.0162	21.1175	21.2024	21.3295	21.07
weight after	20.7151	21.0664	21.1660	21.2376	21.3857	21.11
increase in gram	0.0498	0.0502	0.0485	0.0352	0.0562	0.05
increase in per cent	0.24%	0.24%	0.23%	0.17%	0.26%	0.23%
Hydrothermal + salt	D18	D19	D20	D21	D22	
weight before	21.3071	21.3709	21.3354	21.2886	21.2860	21.32
weight after	21.3760	21.4386	21.3981	21.3443	21.3684	21.39
increase in gram	0.0689	0.0677	0.0627	0.0557	0.0824	0.07
increase in per cent	0.32%	0.32%	0.29%	0.26%	0.39%	0.32%

Average weight before [g]	21.24823
Total [g]	318.7235
Average weight after [g]	21.31333
Total weight after [g]	319.7
Average increase [%]	0.31%

Specimen weight rounded off to two decimals, weights in grams

Static bending

VDA	B8	B9	B10	B11	B12	B13	B14	
weight before	2.60	2.61	2.61	2.60	2.60	2.61	2.60	2.60
weight after	2.61	2.61	2.62	2.62	2.61	2.62	2.61	2.61
increase in gram	0.01	0.00	0.01	0.02	0.01	0.01	0.01	0.01
increase in per cent	*0.38%*	*0.00%*	*0.38%*	*0.76%*	*0.38%*	*0.38%*	*0.38%*	*0.38%*
Hydrothermal	B15	B16	B17	B18	B19	B20	B21	
weight before	2.60	2.59	2.49	2.53	2.55	2.57	2.58	2.56
weight after	2.60	2.60	2.50	2.54	2.56	2.57	2.58	2.56
increase in gram	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01
increase in per cent	*0.00%*	*0.38%*	*0.40%*	*0.39%*	*0.39%*	*0.00%*	*0.00%*	*0.22%*
Hydrothermal + salt	B22	B23	B24	B25	B26	B27	B28	
weight before	2.58	2.58	2.59	2.59	2.59	2.60	2.59	2.59
weight after	2.59	2.59	2.60	2.60	2.60	2.61	2.61	2.60
increase in gram	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
increase in per cent	*0.39%*	*0.39%*	*0.39%*	*0.39%*	*0.39%*	*0.38%*	*0.77%*	*0.44%*

Average weight before [g]	2.58
Total [g]	54.26
Average weight after [g]	2.59
Total weight after [g]	54.45
Average increase [%]	0.39%

average VDA	0,38%
average hydrothermal	0,23%
average hydrothermal + salt	0,39%

Specimen weight rounded off to two decimals, weights in grams

Tensile test

VDA	D6	D7	D8	D9	D10	
weight before	21.33	21.36	21.41	21.40	21.30	21.36
weight after	21.41	21.43	21.49	21.48	21.39	21.44
increase in gram	0.08	0.07	0.08	0.08	0.09	0.08
increase in per cent	*0.37%*	*0.33%*	*0.37%*	*0.37%*	*0.42%*	*0.37%*
Hydrothermal	D13	D14	D15	D16	D17	
weight before	20.67	21.02	21.12	21.20	21.33	21.07
weight after	20.72	21.07	21.17	21.24	21.39	21.12
increase in gram	0.05	0.05	0.05	0.04	0.06	0.05
increase in per cent	*0.24%*	*0.24%*	*0.24%*	*0.19%*	*0.28%*	*0.24%*
Hydrothermal + salt	D18	D19	D20	D21	D22	
weight before	21.31	21.37	21.34	21.29	21.29	21.32
weight after	21.38	21.44	21.40	21.34	21.37	21.39
increase in gram	0.07	0.07	0.06	0.05	0.08	0.07
increase in per cent	*0.33%*	*0.33%*	*0.28%*	*0.23%*	*0.37%*	*0.31%*

Average weight before [g]	21.25
Total [g]	318.74
Average weight after [g]	21.31
Total weight after [g]	319.72
Average increase [%]	0.28%

C Salt submerging in hydrothermal cycle with salt

The table below shows the date the submerging was done, for how long and in which cycle the specimens were removed and placed in the climate chamber. The specimens for bending and tensile tests have very different size and for easier handling were they placed in two different bowls, but with the very same solution (NaCl solution from the VDA). They were removed from the climate chamber directly into the solution and taken direct from the solution to the climate chamber, without drying them.

Date	**Time**	**Starting cycle**	**Ending cycle**
10 May	13:40-14:40 (1 hour)	Beginning of 2nd phase	2nd phase
15 May	13:45-14:45 (1 hour)	End of 3rd phase	1st phase
17 May	14:10-15:10 (1 hour)	1st phase	Beginning of 2nd phase
20 May	8:45-9:45 (1 hour)	2nd phase	2nd phase
24 May	90:10:15 (1 hour. 15 minutes. longer meeting than expected)	2nd phase	3rd phase
27 May	8:30-9:30 (1 hour)	2nd phase	3rd phase

D Calculations static bending

These calculations have been done in order to get a reasonable value to use as a guideline in discussions, and to get an idea of applied forces, and the mid-span deflection of carbon fibre composite. The formulas can be found in ASTM D7264/D7264M-07 (ASTM International, 2007a) and in ASTM D790-07 (ASTM International, 2007b).

Material properties

δ = mid span deflection [mm]

L = support span [mm]

h = thickness of beam [mm]

d = width of beam [mm]

E = Young's modulus/tensile modulus [MPa] (from data sheet)

Material dimensions for static fatigue: $L = 25.4\ mm;\ h = 1\ mm;\ b = 12.7\ mm;$

Applied loads

$\varepsilon =$ the maximum strain at the outer surface

σ = stress at the outer surface in the load span region [MPa]

P = applied force [N]

Maximum strain, three-point configuration

$$\varepsilon = \frac{4.36\delta d}{L^2}$$

Mid-span deflection,

If $\varepsilon = 0.01$

$$\delta = \frac{\varepsilon L^2}{4.36d} = \frac{0.01 \times 25.4^2}{4.36 \times 1.6} = 0.92\ mm$$

Maximum flexural stress, three-point configurations

$$\sigma = \frac{3PL}{4bd^2}$$

$$\varepsilon = \frac{\sigma}{E}$$

$$\sigma = \varepsilon E$$

$E = 67GPa$ from data sheet for woven carbon prepregs, carbon fibres (AGP280-5H) with epoxy resin (Hexcel Composites, 2013). Tensile modulus in 0°-direction at 25°C.

Applied force, when maximum flexural stress and if $\varepsilon = 0.01$

$$P = \frac{4bd^2\sigma}{3L} = \frac{4bd^2\varepsilon E}{3L} = \frac{4 \times 12.7 \times 1.6^2 \times 0.01 \times 67 \times 10^3}{3 \times 25.4} \approx 1143N = 1.1kN$$

E Results from tests

E.1 Static bending

Reference	B1	B2	B3	B4	B5	B6	B7	*Average*	*Standard deviation*
Peak load (N)	1211	1285	1249	1221	1235	1241	1277	1245	27
Flexural strength (MPa)	1098,1	1133,4	1086,2	1059,0	1050,4	1056,0	1076,7	1080,0	29,2
Flexural modulus (M Pa)	51326,5	51900,5	51834,5	51208,0	51515,3	51994,4	51393,8	51596,1	310,6
Strain at peak (mm/mm)	0,022	0,023	0,022	0,021	0,021	0,021	0,022	0,022	0,001
VDA	B8	B9	B10	B11	B12	B13	B14		
Peak load	1203	1246	1267	1271	1272	1226	1310	1256	35
Flexural strength (MPa)	1000,8	1037,8	1041,4	1061,4	1061,4	1015,3	1100,7	1045,5	33,0
Flexural modulus (MPa)	49951,0	50629,9	50718,4	51178,5	51053,9	50421,9	51344,2	50765,8	479,2
Strain at peak (mm/mm)	0,022	0,021	0,021	0,022	0,021	0,021	0,023	0,022	0,001
Hydrothermal	B15	B16	B17	B18	B19	B20	B21		
Peak load	1211	1129	1208	1207	1269	1226	1296	1221	53
Flexural strength (MPa)	1011,1	945,0	1115,4	1062,1	1099,3	1055,2	1099,0	1055,3	60,0
Flexural modulus (MPa)	50091,0	49968,2	52732,4	51529,2	51259,0	51449,5	50714,4	51106,3	952,5
Strain at peak (mm/mm)	0,021	0,020	0,022	0,021	0,023	0,022	0,023	0,022	0,001
Hydrothermal + salt	B22	B23	B24	B25	B26	B27	B28		
Peak load	1256	1222	1301	1270	1176	1308	1248	1254	46
Flexural strength (MPa)	1059,9	1044,8	1093,2	1069,0	988,7	1094,2	1040,6	1055,8	36,3
Flexural modulus (MPa)	50091,8	51520,6	50798,9	50807,6	49903,4	51115,9	50667,2	50700,8	558,8
Strain at peak (mm/mm)	0,022	0,021	0,023	0,022	0,020	0,022	0,022	0,022	0,001

Static bending tests

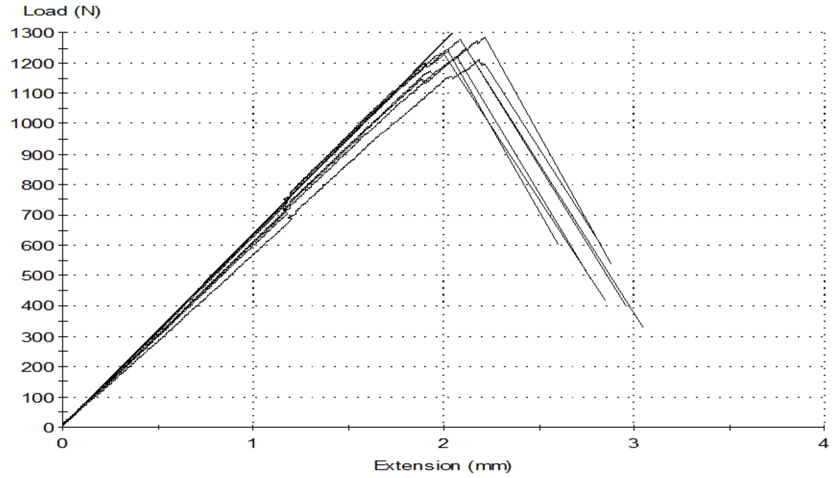

Figure 49. Reference

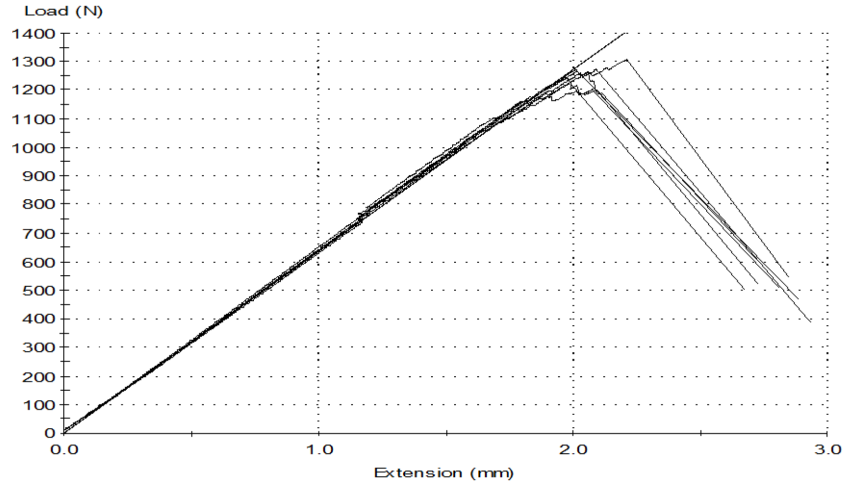

Figure 50. VDA

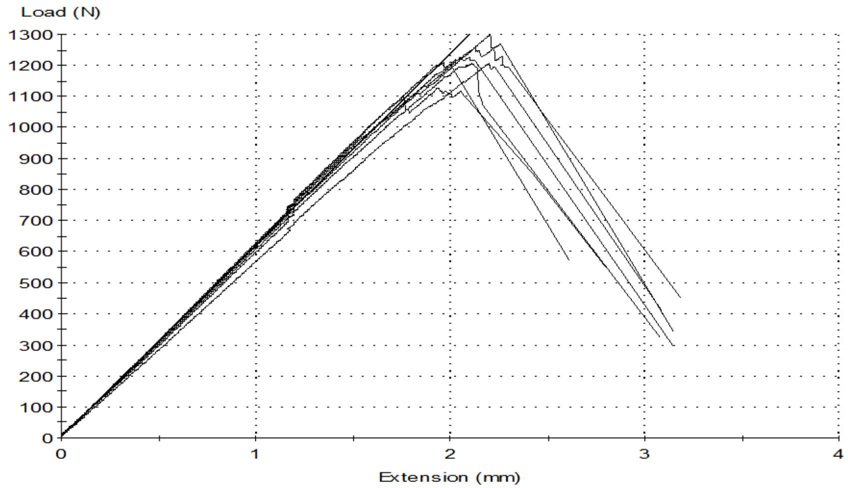

Figure 51. Hydrothermal

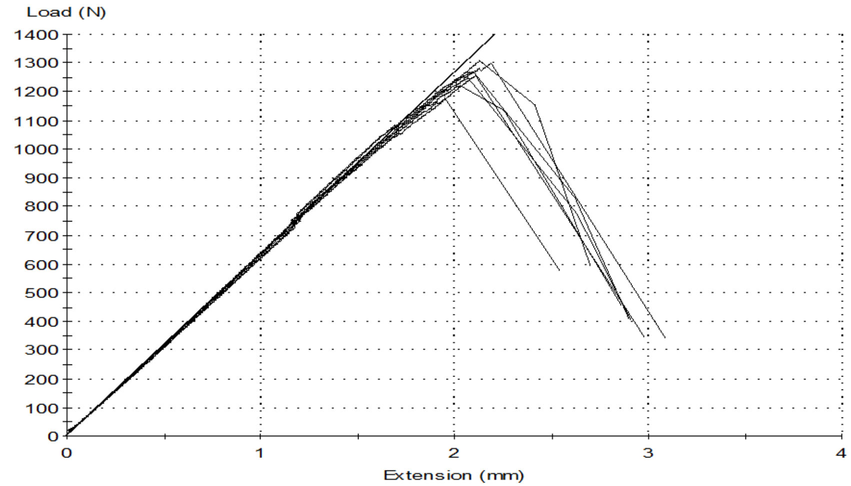

Figure 52. Hydrothermal + salt

E.2 Tensile

Reference	D1	D2	D3	D4	D5	*Average*	*Standard deviation*
Ultimate stress (MPa)	673,4	668,2	671,7	683,5	653,4	670,1	10,9
Ultimate strain (%)	1,34	1,37	1,36	1,41	1,33	1,36	0,03
Modulus (MPa)	49550	49900	48890	49239	48655	49247	499
VDA	D6	D7	D8	D9	D10		
Ultimate stress (MPa)	*683,5*	*693,5*	*684,4*	678,7	680,5	684,2	5,8
Ultimate strain (%)	1,39	1,42	1,39	1,40	1,37	1,39	0,02
Modulus (MPa)	49250	48412	48637	48216	49097	48723	441
Hydrothermal	D13	D14	D15	D16	D17		
Ultimate stress (MPa)	646,2	686,0	672,2	675,5	636,3	663,4	21,10
Ultimate strain (%)	1,26	1,38	1,39	1,41	1,31	1,35	0,06
Modulus (MPa)	51504	49439	48868	48082	49001	49379	1285
Hydrothermal + salt	D18	D19	D20	D21	D22		
Ultimate stress (MPa)	657,9	669,6	652,6	658,8	665,6	660,9	6,7
Ultimate strain (%)	1,37	1,39	1,36	1,36	1,40	1,38	0,02
Modulus (MPa)	47203	47782	47833	48264	47331	47683	425

Tensile test, reference specimens

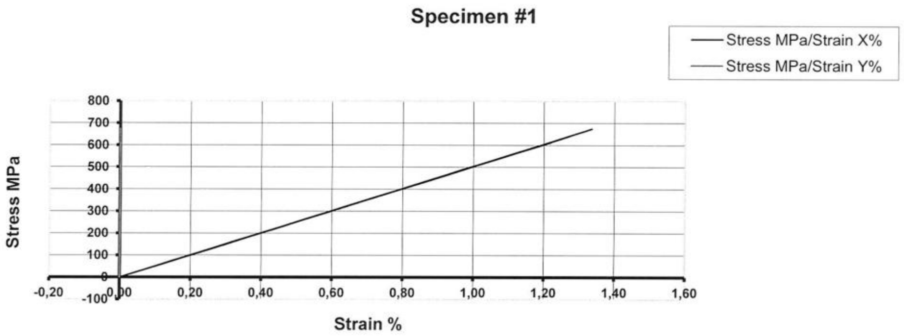

Figure 53. Tensile test, specimen D1

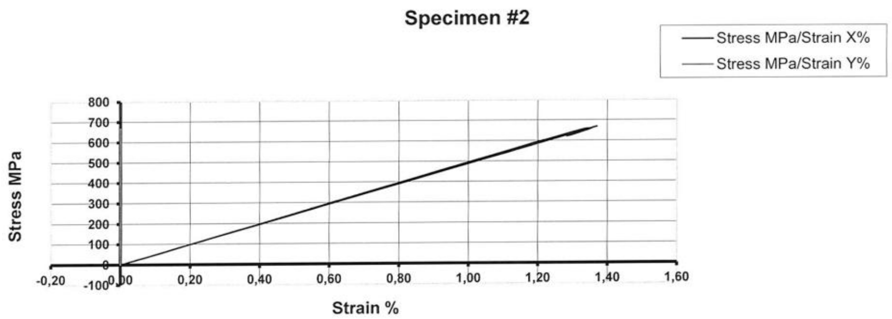

Figure 54. Tensile test, specimen D2

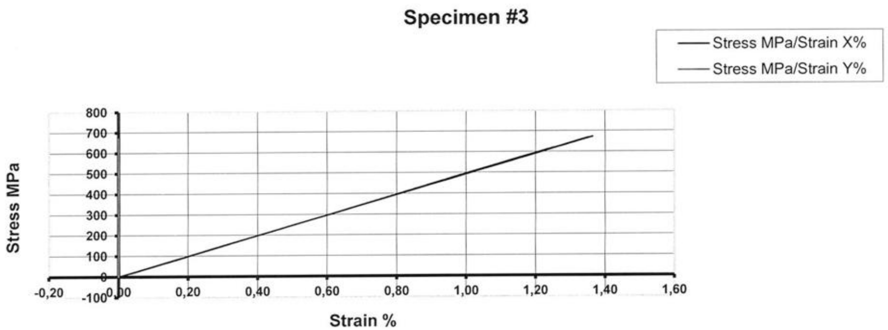

Figure 55. Tensile test, specimen D3

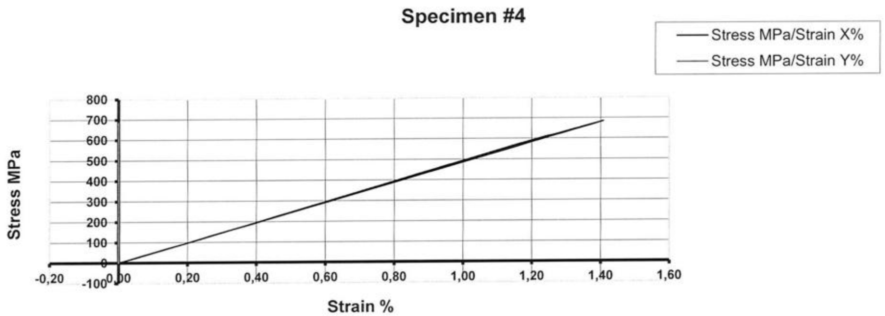

Figure 56. Tensile test, specimen D4

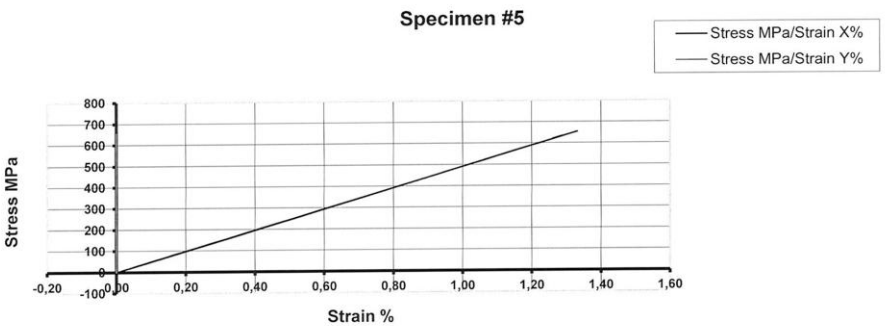

Figure 57. Tensile test, specimen D5

Tensile test, VDA specimens

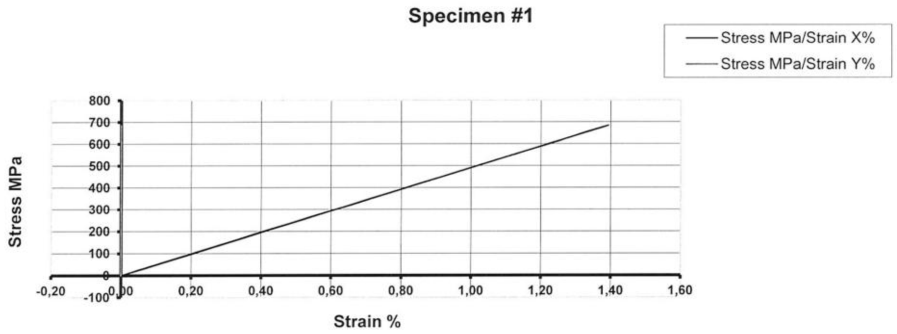

Figure 58. Tensile test, specimen D6

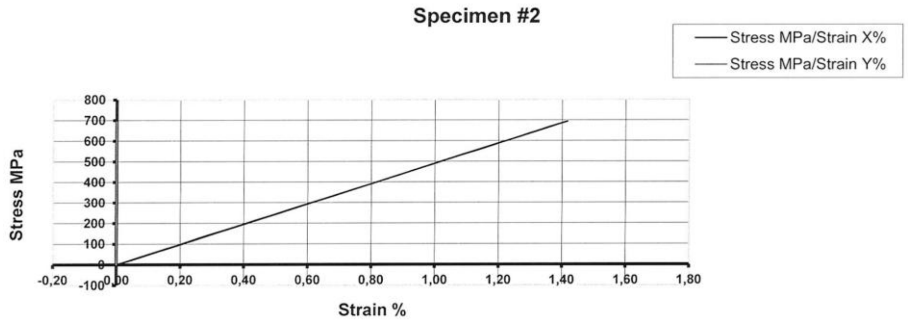

Figure 59. Tensile test, specimen D7

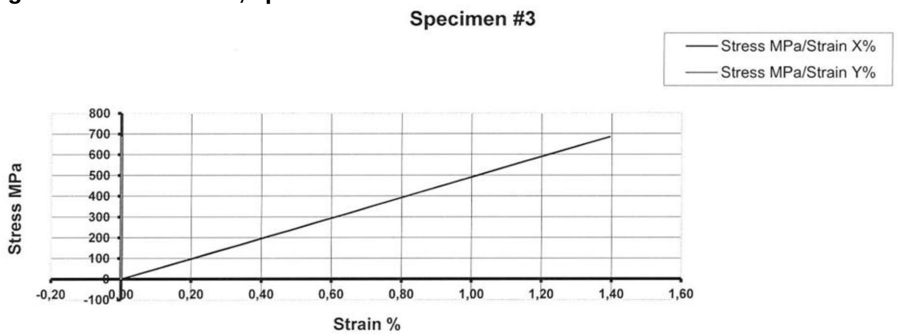

Figure 60. Tensile test, specimen D8

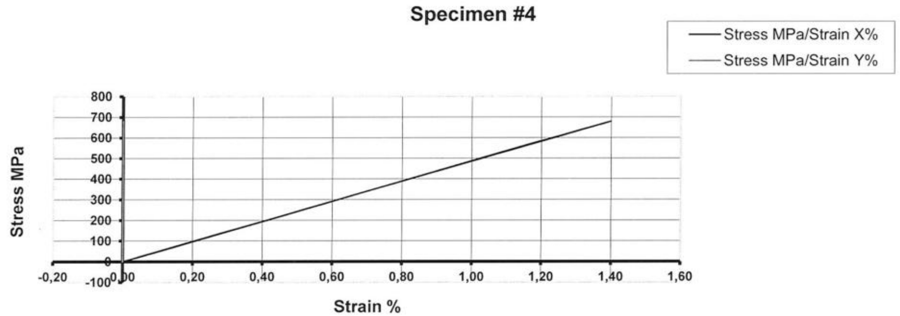

Figure 61. Tensile test, specimen D9

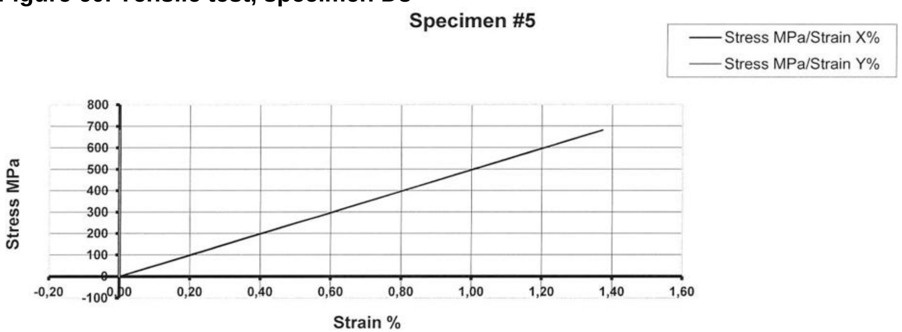

Figure 62. Tensile test, specimen D10

Tensile test, hydrothermal

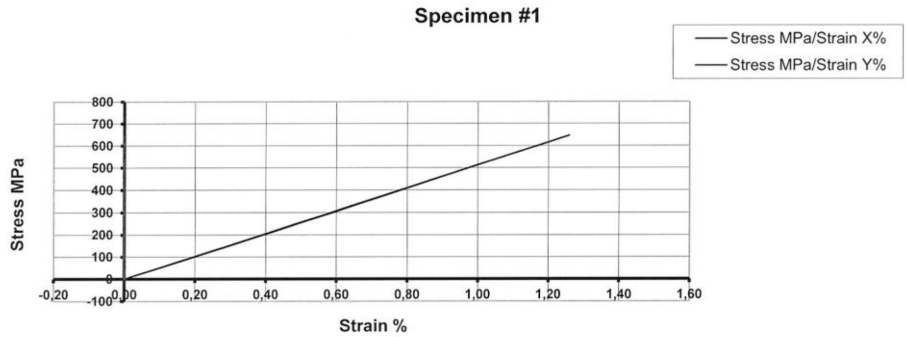

Figure 63. Tensile test, specimen D13

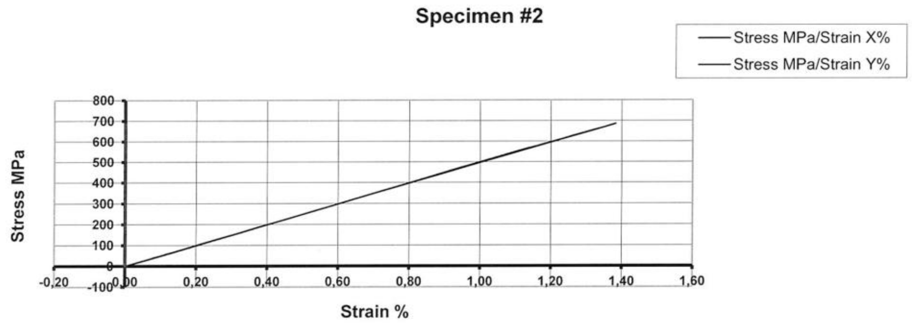

Figure 64. Tensile test, specimen D14

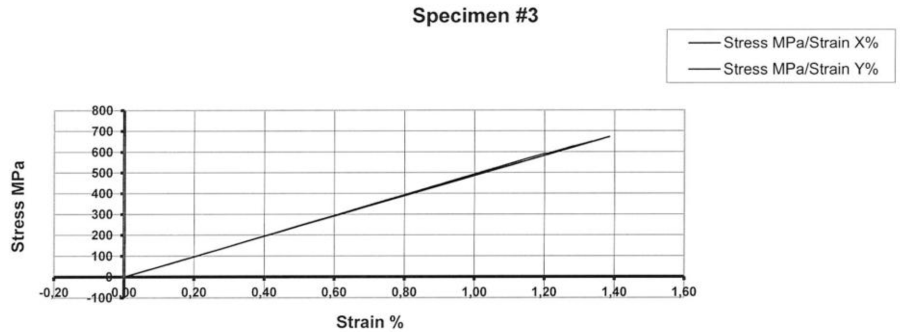

Figure 65. Tensile test, specimen D15

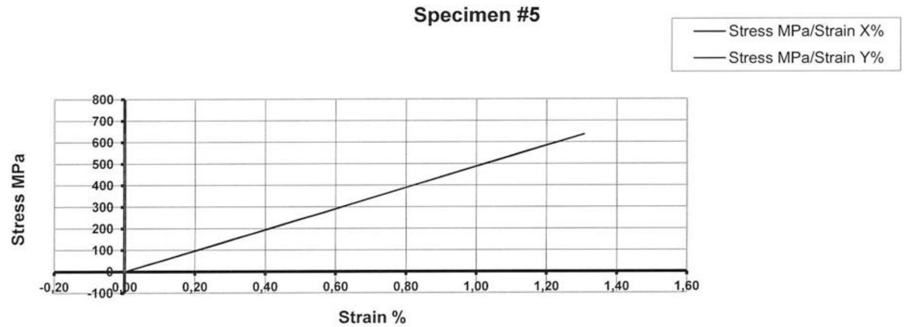

Figure 66. Tensile test, specimen D16

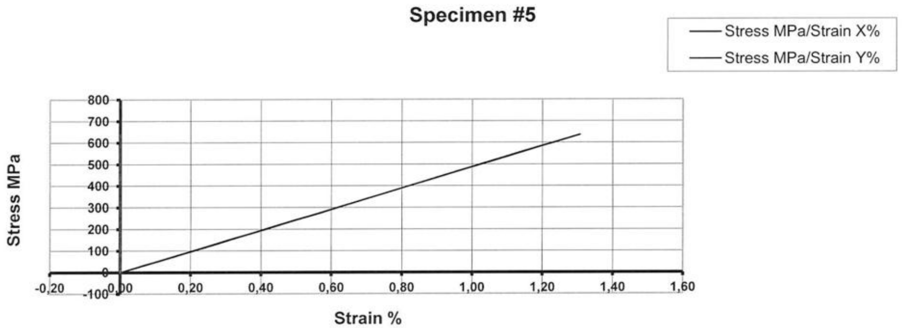

Figure 67. Tensile test, specimen D17

Tensile test, hydrothermal + salt

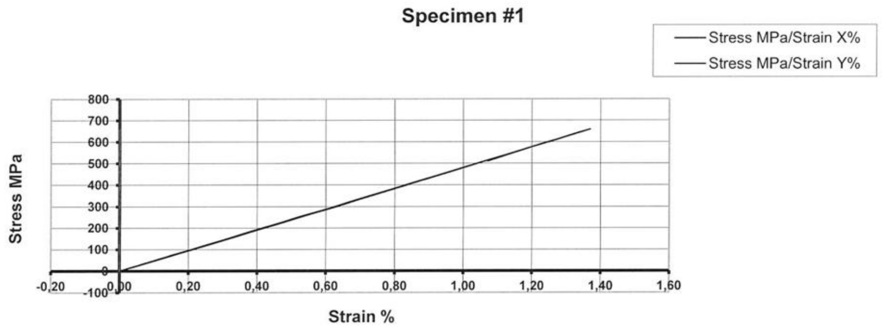

Figure 68. Tensile test, specimen D18

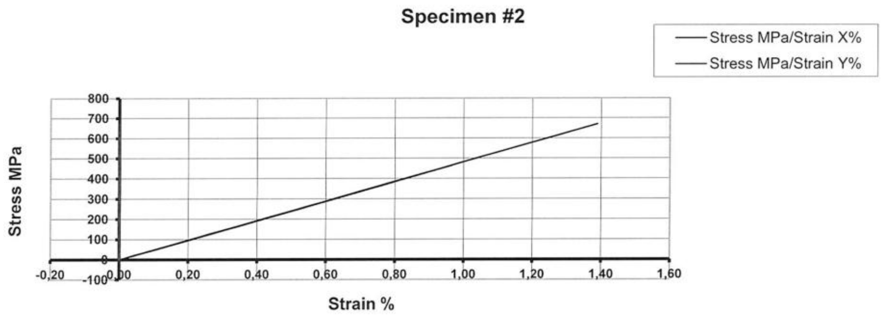

Figure 69. Tensile test, specimen D19

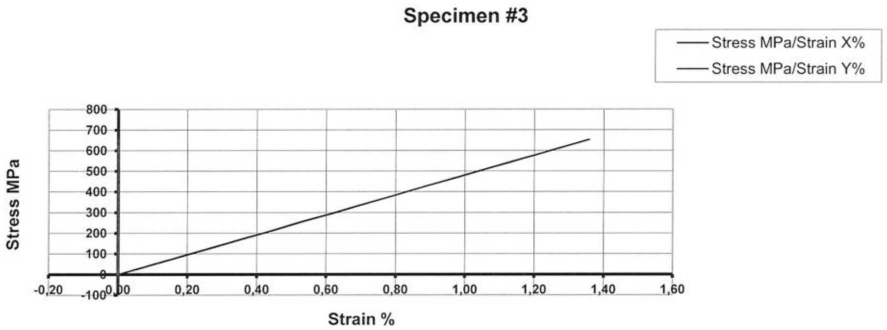

Figure 70. Tensile test, specimen D20

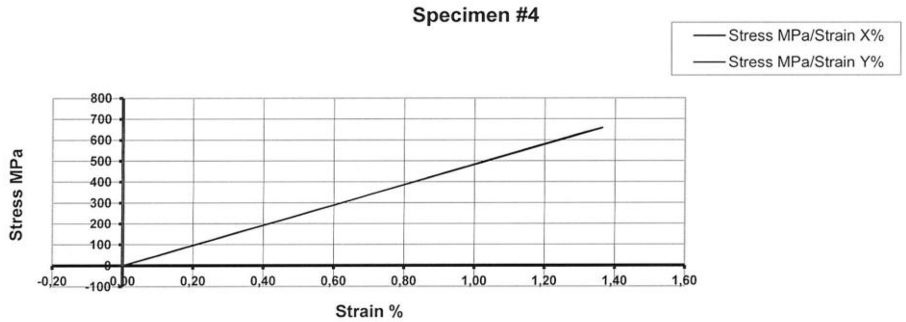

Figure 71. Tensile test, specimen D21

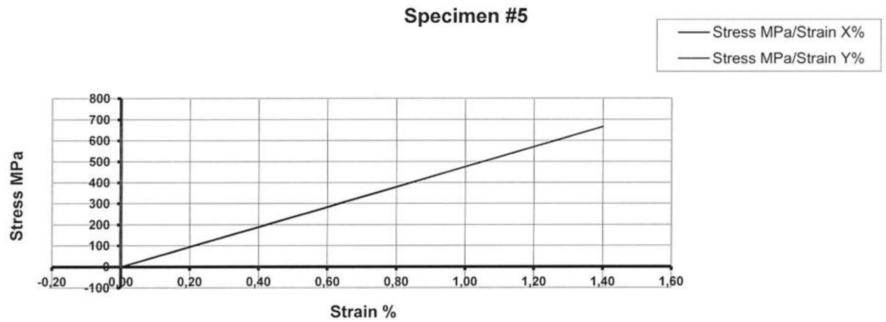

Figure 72. Tensile test, specimen D22