

# **Adhesive bonding between dissimilar materials**

Evaluation of single-lap adhesive bonds between polymer matrix composites and aluminium at varying temperatures, based on tensile shear testing

*Master's thesis in Materials Engineering, 30 HEC*

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Gothenburg, Sweden 2020

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Cover: Test samples of glass fiber reinforced polymer adhered to aluminium with a single-lap bond consisting of an adhesive film.

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## **Abstract**

This master thesis is done at a Defense & Security Company in cooperation with the department of *Industrial and Materials Science* at *Chalmers University of Technology*.

This thesis is an evaluation of adhesive bonds between composite to composite, and composite to metal in different environments. The different environments are simulated only by temperature variations to represent environmental conditions of land, sea and air. The evaluation is done through a literature study and experimental mechanical testing. The literature study resulted in a theoretical background that comprises knowledge about composites, adhesive joints and surface treatments prior to adhesive bonding.

The experimental part of the evaluation is done to determine the tensile shear strength of a single-lap bond, with a test method similar to *ISO4578*. The material combinations tested are mostly based on usability for the Defense & Security Company, resulting in tests of glass fiber reinforced polymer (GFRP) adhered to GFRP, GFRP adhered to aluminium and aramid fiber reinforced polymer (AFRP) adhered to aluminium.

All test series were bonded with the adhesive film, *FM 300-2M*. All combinations were tested in room temperature and at elevated temperature. GFRP to aluminium and AFRP to aluminium were tested after pre-conditioning by temperature cycling. Sandblasting was used as surface treatment for all the test samples. Production of the test samples and the adhesion process were done externally at *Elitkomposit AB* and the tensile shear testing was conducted at the Defense & Security Company.

When bonding GFRP to GFRP the results showed that mechanical joints could be replaced with single-lap adhesive bonds. However, the results from the dissimilar test series were promising as the shear strength was high, but it varied within each test series. Therefore, the mechanical joints can not be replaced based on these results. Further evaluation and testing are recommended in order to replace mechanical joints with adhesive bonds when dissimilar material are used.

Keywords: *Adhesive bonding, tensile shear testing, single-lap, adhesive bond, GFRP, AFRP, Aluminium 6082-T6, Polymer Matrix Composite, Fiber reinforced composite, thermal cycling*



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# Acronyms

**AFRP** aramid fiber reinforced polymer.

**CAA** chromic acid anodizing.

**CFRP** carbon fibre reinforced polymer.

**CTE** coefficient of thermal expansion.

**DSC** Defense & Security Company.

**FRP** fiber reinforced polymer.

**GFRP** glass fiber reinforced polymer.

**IMS** Industrial and Materials Science.

**PAA** phosphoric acid anodizing.

**PMC** polymer matrix composite.

**RT** room temperature.

**T<sub>g</sub>** glass transition temperature.

**T<sub>m</sub>** melting temperature.



# 1

## Introduction

This master thesis was done at a Defense & Security Company (DSC) in cooperation with the *Industrial and Materials Science (IMS)* department at *Chalmers University of Technology*. Supervisor and examiner from department of IMS at *Chalmers* was *Johan Ahlström* and supervisor at the DSC was *Lucy Aksöz Markos*. The project was part of one of the engineering teams lead by *Mattias Skogsberg*.

The project was conducted over a period *20 weeks*, starting *27th January 2020*, and the aim is to hold the final presentation, and to hand in the final report in the middle of *June 2020*. If the master thesis is not complete within *20 weeks* it is possible to prolong it until the end of *August 2020*.

Due to secrecy at the DSC, *two* versions of the report and presentation were made. The disclosed versions will be published and presented at *Chalmers* while the non-disclosed version will be internally published and presented within the DSC.

### 1.1 Background

The applications of composite materials are expanding at a fast pace. Using composite structures enables light-weight designs with high strength and stiffness. By combining materials, the final composites can have adjusted properties to its specific application. These qualities make composites interesting, and enhance their applicability even more in the future .

By replacing mechanical joints with adhesive bonds in constructions, several advantages can be obtained. The load gets more evenly distributed along the bond, and not as concentrated as in the mechanical joint. Adhesive bonding enables less weight, and improves other properties such as damping. The success and usability of adhesive bonding between composites to composites and composites to metals is however limited. Limitations include mismatch in thermal expansion and environmental resistance of the polymer.

### Industrial background

The Defense & Security Company is investigating if the mechanical joints can be replaced with adhesive bonds in some of their composite structures. The replacement of mechanical joints could to some extent, and when possible, simplify the construc-

tion and assembly process, as well as lower the total weight of the component.

The specific process that gave rise to this thesis was a mechanical joint between a composite part and an aluminium part for a aerospace component at the DSC. The product is made up of a shell and requires the possibility to transmit microwaves. Earlier testing has been conducted to verify the properties in an adhesive bond between a glass fiber reinforced polymer system to aluminium for the same product. When performing the process according to standards, the bonding passed the requirements for the product. Even though the results were considered promising, the DSC decided not to apply this solution to the product. Instead, they choose to use a bolt joining solution.

Different solutions to the material system with different composite combinations have been considered. Revisions of the construction has been done, but the mechanical joints are still used. The revision process raises again the question if adhesive bonds could replace the mechanical joints between a composite part and a aluminium part for this component. The situation around the product has made it clear that more evaluation has to be done on the subject of adhesive bonding of composites to metals at the DSC.

## 1.2 Purpose

The purpose of this master thesis is to evaluate the performance of adhesive bonds, used for bonding composites to composites, and composites to metals. The material combinations have to be evaluated at conditions simulating different environments, such as land, sea and air.

The foundation of this master thesis is to gain knowledge of how different materials behave when bonded together by adhesives depending on the temperature they are exposed to. This will be evaluated by a literature study but also through mechanical testing. This master thesis will result in an analysis if the chosen material combinations, when bonded with adhesive, could replace a mechanical joint.

### 1.2.1 Clarification of Questions

After finding out which combination of materials, is most frequently used at the DSC, these research questions will be answered within the end of the project:

*R1:* What are the advantages and limitations by applying an adhesive bond, at varying temperatures, for dissimilar materials?

*R2:* Which surface treatment is the optimal for the chosen material combinations, when bonded with an adhesive?

*R3:* Can the performance of an adhesive bond be sufficient to replace a mechanical joint for chosen material combination?

### 1.3 Delimitations

The following delimitations will be applied to the master thesis.

- **The composites, metals and adhesives, for the mechanical testing, will be limited to the ones already used at the DSC.**  
This is mainly due to the possibility of long lead times, risking that the materials will not be available for the mechanical testing.
- **This master thesis will be conducted over a period of 20 weeks.**  
If the thesis is not finished within this period there is a possibility for an extension until *31th of August 2020*.
- **The mechanical testing will be limited to those available at the DSC.**  
If the necessary equipment is not available then the testing has to be conducted externally, as long as it fits the time frame.
- **The objective is to benefit design and production at the DSC.**  
To focus the research and mechanical testing around the combination of materials that are used in the products at the DSC. This is done to limit the scope and still keep the utility.
- **The environmental differences will depend purely on temperature.**  
The environmental aspects can be mechanical- or climatic environments. For this master thesis, the environments for land, sea and air will only differ in temperature for testing and pre-conditioning.



# 2

## Theoretical framework

This chapter consist of information obtained from the literature study. General information will be presented about composites and adhesives that are of interest in the project. The theoretical background also includes different surface treatments used prior to adhesive bonding. The opportunities and limitations by replacing mechanical joints with adhesive bonds will be researched and presented in this chapter.

### 2.1 Composites

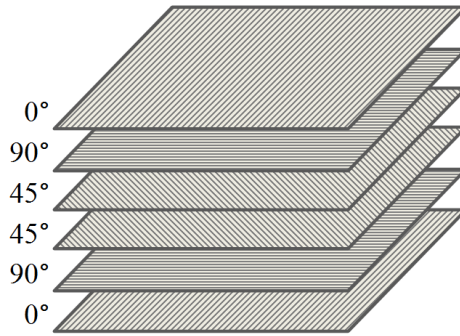
The need for materials with improved overall performance has lead to combining different materials in order to satisfy the requirements which are set by the users. A composite material is a combination of *two* or more materials with different properties. By combining them, it is possible to create a material with characteristics that are different from the starting constituents. Due to the wide range of different constitutionals and endless combinations, composites have an extraordinary design flexibility (Chawla, 2019, pp. 4–6).

Composites consist of a matrix and a reinforcement material. The reinforcement usually determines the strength and stiffness of the composite, while the matrix provides the ductility and the light-weight. The composite can be built of different constituents, the one of interest in this master thesis is matrices made of polymers, referred to as polymer matrix composite (PMC). Other kinds of composites are Metal Matrix Composites (MMC) and Ceramic Matrix composites (CMC). Composites have become of major interest in aerospace and aircraft industry due to their advantages over metals, primary their superior stiffness-to-weight and strength-to-weight ratio (Miracle and Donaldson, 2001c).

Most composites that are used for high-performance applications are made from synthetic materials. How a certain composite will perform depends on the geometry, the amount of the constituents and properties of the constituents. The strength and stiffness can be increased by adding a higher amount of reinforcement (Staab, 2015, pp. 2–3).

**Prepregs** are a common form of PMC and is the composite used in products at the DSC, consequently this master thesis emphasis prepregs. A prepreg is a thin lamina with pre-impregnated reinforcement fibers, in a partially cured resin. The reinforcements are usually long continuous fibers, either unidirectional or of a weave

type. The polymer matrix in the prepreg is not fully cured, therefore it allows for easy handling. However, the prepregs need to be stored in low temperatures to not initiate the curing process. A typical prepreg comes in the form of a roll that is  $300\text{-}1.500\text{ mm}$  wide, approximately  $0.125\text{ mm}$  thick and  $50$  to  $250\text{ m}$  long (Ashby, Shercliff, and Cebon, 2014). Common manufacturing processes are hand- or machine-layup. The material is cut and laid up, layer by layer to produce a laminate. The thickness of the laminate is adjusted by the number of layers, and the orientations of the ply determines the stiffness of the built-up structure. After the laminate is formed to the desired shape, it is cured in an autoclave with heat and pressure (Gauthier, 1995). Fiber reinforced polymer (FRP), such as prepregs, are highly anisotropic, which means that their mechanical properties are strongly dependent on direction. When making components of several layers of prepregs the anisotropy can be compensated for by arranging the plies in different orientations, called a cross-ply laminate. The orientation of the plies are at a given angle from the loading axis, see figure 2.1.



**Figure 2.1:** Prepreg plies oriented in different directions creating a cross-ply laminate

**Autoclave** process is one of the most common curing methods of creating composites within the aerospace industry. Differing gas pressure is the basic principle that is used when forming with an autoclave. The process begins with placing the prepregs in the chosen directions and thickness. The air is then drawn out of the laminate with the help of a vacuum bag. The enclosed structure is then placed in the heated pressure vessel for a specific time, pressure and temperature. Due to the high pressure that can be obtained, it is possible to create parts with less porosity and voids than when cured in an oven (Campbell, 2007b, pp. 17–18). Due to the gas pressure being applied isostatically there are few limitations to the different shapes that can be cured (Campbell, 2007a, pp. 176–177).

### 2.1.1 Matrix properties in polymer matrix composite

Polymers are a common matrix used for composites, mainly due to their low weight and cost. The matrix binds the embedded fibers together and transfers the load to, and between the fibers. Furthermore, the matrix controls the environmental resis-



tance and protects the fibers against abrasion and handling (Gauthier, 1995). The reinforcement can be used to its full potential due to the matrix holding the fibers in the proper orientation and position. Because polymers have a limited usability in high temperatures, the matrix is determining the service temperature of the composite (Miracle and Donaldson, 2001c, pp. 8–9).

In general, a polymer can fall into two different categories depending on how it reacts to heat, thermoplastic or thermoset. A thermoplastic polymer will soften and melt when heated and harden when cooled, and can due to this be remelted and reformed multiple times. Thermoset polymers form cross-links during polymerization that limits the chain movement, and thereby generally making the polymer stronger and more rigid than a thermoplastic (Chawla, 2019, pp. 78–79). This network of polymer chains in thermosets degrade without entering a liquid stage, and can thereby not be remelted as thermoplastics can (McKeen, 2017, pp. 29–30).

**Glass transition temperature ( $T_g$ )** is the temperature where a polymer changes from being hard and relatively brittle, to becoming softer. This property partly determines which application a polymer is suitable for. To use a polymer for structural purposes above its  $T_g$  is not recommended. The  $T_g$  does not represent a thermodynamic phase transformation, but many physical properties change drastically at the  $T_g$ , e.g. viscosity, heat capacity, elastic modulus and coefficient of thermal expansion (CTE) (Chawla, 2019, pp. 77–78). The  $T_g$  is not one well defined, rather it takes place over a broad temperature range. The decrease in mechanical properties that occurs at  $T_g$  for a polymer matrix, means that it can no longer effectively transfer load to, and in between reinforcements. The  $T_g$  is therefore an important property to be aware of in order to know the upper temperature limit for a PMC.

The  $T_g$  limits what applications polymeric materials can be used in. Polymer matrices are sensitive to moisture, which can alter their properties. Due to this, a somewhat lower temperature range is typically chosen as a maximum for certain applications, where a margin of safety is needed. The aerospace industry has established a material operational limit (MOL) to reduce the  $T_g$  by a prescribed value, usually by  $28^\circ\text{C}$ . For applications that will be in a moist environment two different  $T_g$  are determined. One of them without any moisture conditions, resulting in a dry  $T_g$ , and one using test specimens that have been moisture conditioned, resulting in a wet  $T_g$  (Adams, 2018).

#### 2.1.1.1 Matrix Materials

The matrix for PMCs are mostly made up of thermosets, however thermoplastics can also be used. The prepregs at the DSC are only made of thermoset matrices, due to that they generally have superior mechanical- and thermal properties as well as being well established within the industry.

Epoxy is the matrix which is most frequently used at the DSC. Other materials that are of interest for this project, as they can have preferable properties com-

pared to epoxy, are *Cyanate Ester*, *Polyimide*, *Bismaleimide* and high-temperature thermoplastics.

**Epoxy** is the most used thermosetting matrix in structurally demanding applications, especially within aerospace (Miracle and Donaldson, 2001d). Epoxy resin covers a broad group of thermosetting polymers, where the primary cross-linking occurs through the reaction of an epoxide group, and therefore it can be modified to fit multiple applications (Boyle, Martin, and Neuner, 2001). The elongation to failure is rather low for epoxy but otherwise it has a combination of desirable properties, high strength, low shrinkage, low toxicity, excellent adhesion, and low cost. It can be partially cured and used as matrix for prepregs. The maximum service temperature for structural applications is set to be around  $120^{\circ}C$ , due to the possibility of moisture absorption (Gauthier, 1995).

**Table 2.1:** Some important characteristics of epoxy (Chawla, 2019, p. 84)

Density, $\rho$ ( $g/m^3$ )	Strength, $\sigma$ ( $MPa$ )	Modulus, $E$ ( $GPa$ )	Poisson's ratio, $\nu$	CTE, $\alpha$ ( $10^{-6}K^{-1}$ )	Cure shrinkage, (%)	Service temp, ( $^{\circ}C$ )
1.2-1.3	50-125	2.5-4	0.2-0.33	50-100	1-5	120

In order to improve the properties of epoxy post-curing can be utilized. The properties of cured epoxy is highly influenced by the curing temperature and the conversion. The conversion is the amount of cross-linking that occurs during curing. This cross-linking process can be completed with the help of short periods of post-curing at low temperatures. Post-curing leads to a more stable polymer and relaxes the network of cross-links. The mechanical stability is improved by increasing the amount of cross-link and the relaxation of the network could increase ductility, which leads to increased energy absorption before fracture. The mechanical properties and  $T_g$  have been shown to improve until the cross-linked network is fully formed. Temperatures above this point will most often not lead to any further improvements (Carbas et al., 2013).

**Cyanate Ester, Polyimide and Bismaleimide** are high-temperature polymers. Used as matrices these polymers are commonly used for high-temperature applications and tend to be rather expensive.

Cyanate Esters (CEs), also called cyan esters or polycyanurates, have many desirable characteristics that can justify their higher cost compared to epoxy. They have better thermal performance, and have properties more applicable for electrical applications. The moisture absorption and shrinkage on curing is also lower. Application areas for CE are mainly in electronics, printed circuit boards, satellite, radar and aerospace structural components (Robitaille, 2001).

Polyimide (PI) matrices are used when good high-temperature thermal stability are required. The thermal properties of PI matrices are even greater than that of CEs. PIs can come in the form of either thermosetting or thermoplastic, however ther-

mosetting are more common (Miracle and Donaldson, 2001d).

Bismaleimides (BMIs) are a class of thermosetting polyimides with excellent properties. They have good mechanical and electrical properties, and have higher service temperatures than epoxy. Big advantages BMIs have are that they can be processed in a similar way as epoxy using an autoclave (Miracle and Donaldson, 2001a).

**Thermoplastic resins** as the matrix for PMCs are at low use but of high interest. Most thermoplastic matrices are used in applications where the service temperature are rather low. Less than a dozen thermoplastic polymers have been considered for high-temperature applications. What have been prohibiting their prosperity in the field of engineering applications have been the relationship of high-temperature properties to processing. The  $T_g$  and melting temperature ( $T_m$ ) are high, this makes these thermoplastics promising for high-temperature applications. However, the mechanical properties decrease when these temperature points are approached. To have good properties at a certain temperature, the  $T_g$  and  $T_m$  has to be well above the intended service temperature. To be able to form and shape a thermoplastic, the temperature has to be above  $T_g$  or close to  $T_m$  in order for the thermoplastic to be soft enough. In conclusion, thermoplastic matrices require very high processing temperatures compared to thermosets. The lack of tackiness for thermoplastic prepregs is another hindrance that differentiate it from the manufacturing process of thermosets. Some differences between thermoplastic and thermosetting resins can be seen in table 2.2. Thermoplastic that are suitable for high-temperature applications are Polyetherimide (PEI), Polyether etherketone (PEEK) and Polyetherketone ketone (PEKK) (McKague, 2001).

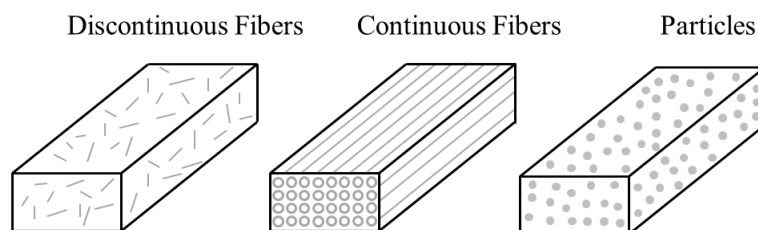
An advantage of thermoplastic parts is that they can undergo post-forming and remelting. This enables fusion bonding and can therefore be assembled without mechanical bonding, or adhesive.

**Table 2.2:** Comparison of high-temperature thermoplastics and thermosets (McKague, 2001)

Characteristic	Thermoplastics	Thermosets
Tensile properties	Excellent	Excellent
Stiffness properties	Excellent	Excellent
Service temperature	Good	Good
Dielectric properties	Good to Excellent	Fair to Good
Environmental weakness	None, or hydraulic fluid	Moisture
Processing temperature	343 - 427°C	121 - 315°C
Lay-up characteristics	Difficult	Easy
In process joining options	Co-fusion	Co.cure, Co-bond
Postprocess joining options	Fastening, bonding, fusion	Fastening, bonding

### 2.1.2 Reinforcements used in polymer matrix composite

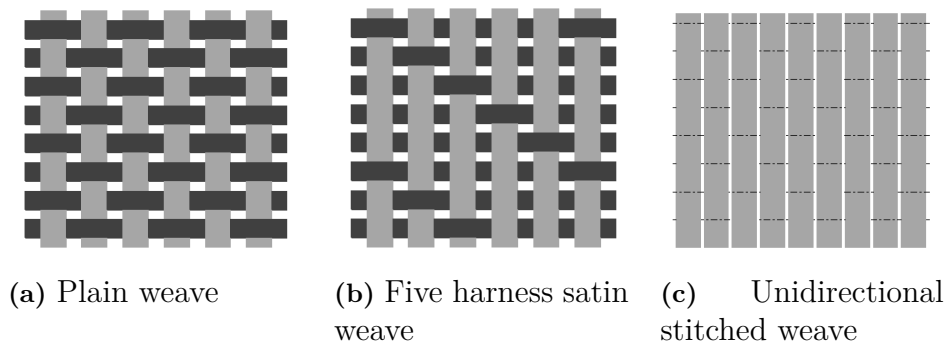
Reinforcements in composites can come in different forms like discontinuous fibers, continuous fibers and particles, see figure 2.2. Fibrous form, referred to as fiber reinforced polymer (FRP), is however most common which is mainly due to the increased strength and stiffness of fibers compared to the other forms. Fibers can have a small diameter when compared to its grain size which makes it possible to gain a higher theoretical strength than what can be achieved in bulk form. Due to the high ratio between length and diameter, a large part of an applied load can be transferred to the fibers through the matrix (Chawla, 2019, pp. 7–16).



**Figure 2.2:** Some common forms of reinforcement used in polymer matrix composite (PMC)

**Fabrics** come in the form of a roll and are made out of reinforcement fibers. Depending on the directions of the fibers and which structure they are made up of, other terms can be used, such as mat, veil and tissue (Bank, 2006). Mats consist of either discontinuous or continuous fibers that are randomly arranged and can therefore be assumed to have isotropic properties in all directions. For structural applications, woven fiber fabrics are more common to use, and especially in the aerospace industry (Miracle and Donaldson, 2001b). Fabrics have, compared to mats, a high anisotropy, but how much depends on how the fibers are arranged. There are some basic weaves, but combinations of different types allow for hundred of variations (Miracle and Donaldson, 2001b). The most common weave type is the plain weave, where the fibers are arranged one up, one down, see a) in figure 2.3.

For satin weaves the fibers periodically skip over several yarns. They are usually produced as four-, five- or eight harness forms, see b) in figure 2.3 for five harness satin weave. The satin structure creates looseness and thus can be easily used for complex and curved structures. Another type of fabric is the stitched fabric, where unidirectional layers of continuous fibers are stitched together, see c) in figure 2.3. This type provides a very high strength in one direction, but also makes it the most unbalanced, with highest anisotropy. A common type of stitched fabrics are biaxial weaves, where the weave consist of two unidirectional fabrics sewn together at an equal percentage of both directions, e.g.  $\pm 45^\circ$  (Bank, 2006).



**Figure 2.3:** Weave types in fabrics

**Glass fiber** is a collective name for a wide range of materials that differ in their chemical composition. Composites with glass fibers as reinforcement in polymer matrix are referred to as glass fiber reinforced polymer (GFRP). Glass fibers are made up of silicon oxide in combination with other oxides like boron, aluminium, iron, calcium and sodium. Depending on the amount of each oxide, they can be divided into three categories, E-, C- and S-glass. E-glass is commonly used because of its properties regarding electrical insulation, C-glass is better at protecting against corrosion and S-glass can resist elevated temperatures better than other glass fibers (Chawla, 2019, pp. 11–15).

Glass fiber has an excellent strength-to-weight ratio. The price of glass fiber is rather low and it can be obtained in a wide range of different forms. One of the limitations is that the fiber strength can decrease when in contact with moisture (Chawla, 2019, pp. 15–16).

Quartz/Silica( $SiO_2$ ) fibers are commonly used for high-temperature applications. They can be categorised based on how much silica they contain. Ultra-pure silica glass fibers (99.99%  $SiO_2$ ) are not only used because of their resistance against high-temperature degradation but also because of their great transparency to longer wavelength and ultraviolet radiation (Wallenberger, Watson, and Li, 2001, p. 30).

**Aramid fiber** is a collective name for aromatic polyamide fibers. Some of the more well-known names are *Kevlar* and *Twaron* (Chawla, 2019, p. 42). Aramid fibers have a low density and high stiffness. They are anisotropic which gives them poor properties in compression compared to tension. Aramid fibers should therefore be avoided for applications where high compressive forces are present. Furthermore, the damping properties of aramid fibers are excellent. The damping properties can be quantified in a unit called logarithmic decrement. A composite made up of AFRP has five times the logarithmic decrement of a composite consisting of GFRP (Chawla, 2019, p. 50).

One of the drawbacks with aramid fibers is that they are sensitive to ultraviolet (UV) light. Exposure to UV-light can cause a decline in mechanical properties as well as cause discolouration of the fibers. Unprotected aramid fibers should thus be

avoided for outdoor applications. The harmful wavelength of radiation could also come from fluorescent lamps or sunlight through window glass, but only in small amounts (Chawla, 2019, p. 52).

Aramid fibers also absorb larger amounts of moisture compared to carbon- or glass fibers. For aerospace applications, there are often metal layers which can protect the AFRP and limit the amount of moisture absorption. Moisture accesses through the free edges, so different types of sealants could also limit the absorption amount (Afaghi, Ye, and Mai, 2000, p. 10).

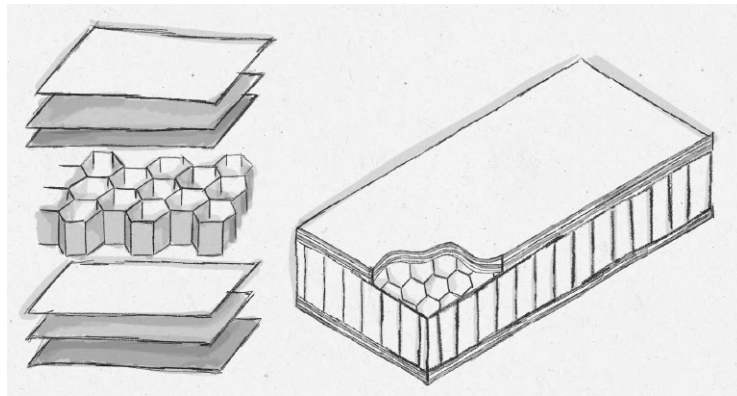
**Carbon fibers** are reinforcements with a carbon amount of at least 90%. Some of the advantages of carbon fibers are their low density, high tensile strength, high stiffness and excellent resistance against chemicals. By combining carbon fibers with a suitable polymer matrix, carbon fibre reinforced polymer (CFRP), it is possible to create a part that is lighter and have higher mechanical properties than metals and other composites. The aerospace and defence industry is one of the main areas where carbon fibers are implemented but they are also on the rise within the automotive industry (Pusch and Wohlmann, 2018, p. 31).

Carbon fibers are built of a strong longitudinal backbone, which gives them high strength and low creep, among other properties. Furthermore, the fibers provide great damping properties against vibrations which is required in certain industrial and aerospace applications. The low thermal expansion of carbon fibers makes them useful in applications where a large temperature range is present. (Pusch and Wohlmann, 2018, pp. 37–38).

### 2.1.3 Sandwich construction

A sandwich composite structure is made up of a thick and lightweight core in between two stiff laminates. A composite that is built this way has good bending stiffness in combination with a low weight. The core usually has great thermal- and electrical insulating properties. Therefore the whole sandwich structure can be seen as an excellent thermal insulator and damper against certain acoustic frequencies. (Karlsson and Åström, 1997, p. 97)

Some common areas where sandwich constructions are used are building panels, aircrafts and boats. Prepregs are typically used for the outside laminates while honeycomb or foam are some common core materials. In figure 2.4, a sandwich construction with a honeycomb core is illustrated. Depending on the combination of core and laminate, different properties can be obtained. Some properties that are sought after are good mechanical and thermal properties, low cost, thermal and acoustic insulation, easily formed and fire resistance (Karlsson and Åström, 1997, p. 97).



**Figure 2.4:** Sandwich construction built up of laminates and honeycomb core

The most common core material is expandable foams. They are usually made out of thermosets but almost all polymers can be made into foams. *Polystyrene*, *polyphenolics* and *polyvinyl chlorides* are some of the most popular foams and they are manufactured by pre-foaming them into blocks. Some polymers, for example *polystyrene*, can be foamed instantly between the faces. This is called *in situ foaming* and can eliminate the step of complex machining or forming (Karlsson and Åström, 1997, p. 97).

When it comes to aerospace applications, the most used cores are honeycomb cores. Honeycombs can be made from a wide variety of materials, such as FRP, unreinforced polymers and sheet metals. Aramid fibers soaked in phenolic resin, also called by the brand name *Nomex*, or aluminium are the most common materials to use for honeycomb cores (Karlsson and Åström, 1997, p. 97).

Creating sandwich structures can be made in two different ways when prepregs are used. Either, prepregs can be placed straight on the core and manufactured as one single component, or the laminates can be created separately and bonded to the core with adhesives. There are a wide range of different methods for creating sandwich structures as a single component, without using adhesives to attach the laminates. Wet lay-up and prepreg lay-up are two of those type of methods and both of them commonly utilize autoclave to cure the sandwich composite (Karlsson and Åström, 1997, pp. 98–101).

## 2.2 Adhesive bonds

Adhesion is described as two surfaces that are held together using interfacial forces. This could be with the help of valence electrons, interlocking actions or both. There are two mechanisms in work for adhesive bonding, which are mechanical interlocking and chemical bonding. Mechanical adhesion makes use of a rough surface and adhesive to secure the parts to each other. Porous materials or materials with cavities are therefore the only types that can make use of mechanical adhesion. Both surface preparation and which adhesive that is used are of equal importance when

mechanical adhesion is needed (Çoban et al., 2019).

One of the main benefits with adhesives bonds compared to mechanical joints, like screws, bolts and rivets, is that the stresses are distributed evenly across the adherends. The strength for mechanical joints are limited to the area where the joints are located. Adhesives are also useful for application where temperature variations are present. Differences in thermal expansion for the adherends could cause unwanted stresses at elevated temperatures when joining materials. By using a flexible adhesive, i.e. low stiffness, it is possible to accommodate for the strains and avoid damage that could occur for a stiffer bond. The lower weight of an adhesive bond compared to one of the mechanical fasteners is also beneficial and enables a light-weight design. Especially for FRP, adhesive bonding has a great advantage over mechanical joints. By not having to make holes for rivets and screws, damaging the load-bearing fibers in the FRP can be avoided (Ebnesajjad and Landrock, 2015a, p. 2).

Even though adhesive bonds could be used to replace mechanical joints for many applications, there are still some drawbacks. In order to create durable bonds, thorough surface preparation is required. It is also crucial to clean all the contaminants, that are left from the surface preparation, which could be detrimental to the strength of the bond. Furthermore, the cure times could be long, especially for adhesives that require high curing temperatures. Ovens, fixtures and presses are essential, which is not necessary for most other mechanical joining methods. (Ebnesajjad and Landrock, 2015a, p. 4).

Adhesive bonds can be divided into two main categories, structural and nonstructural adhesives. Structural adhesives are used for applications where the adherends need to withstand large stresses. The bonds are required to deal with the stresses for the entire service life of the part, which could in some cases be several years (Ebnesajjad and Landrock, 2015a, pp. 1–2). There are no unified rules to determine when an adhesive is thought of as structural. The most common method of determining if an adhesive is structural is if it exceeds  $6.9\text{ MPa}$  in tensile shear testing, using the standard *ASTM D1002* (Hartshorn, 1986, p. 2).

Nonstructural adhesives do not have to fulfill any of the requirements that structural adhesives are evaluated by. Rather they are used for bonding light-weight materials where the strength of the adhesive bond is less of a factor. (Ebnesajjad and Landrock, 2015a, pp. 1–2).

### 2.2.1 Stresses of adhesive bonds

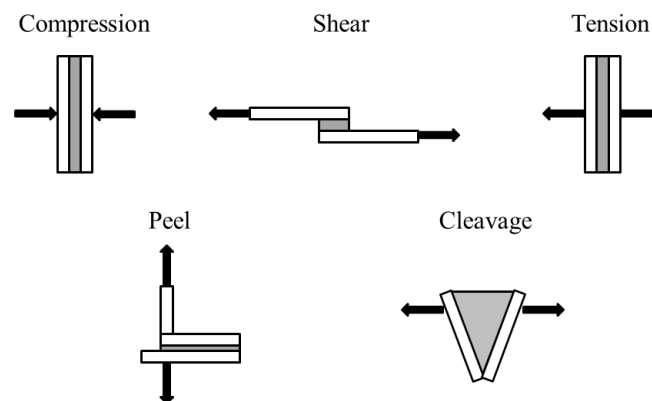
Adhesive bonds can experience different kind of stress, which can be divided in five categories, seen in figure 2.5. The five types are compression, tension, shear, peel and cleavage. It can either be purely one type of stress or a combination of different ones (Ebnesajjad and Landrock, 2015b, pp. 183–185).

- **Compression:** An adhesive bond is the strongest when under compression.



However, this type of stress is not commonly encountered for applications where adhesive bonds are used.

- **Shear:** For this type of stress, the load is evenly distributed across the adhesive bond. Because of this, the bond is fully utilized and therefore failure is less likely to occur.
- **Tension:** Stresses in this case is similar to that of shear, as the load is evenly distributed over the bond area. This advantage of even distribution is however lost if any angular offset of the load is present. For these cases cleavage or peel are most likely to occur together with tension.
- **Peel:** This type of stress only develops if one or both of the adherends are flexible. Adhesive bonds are typically sensitive towards this type of stress.
- **Cleavage:** Stress from cleavage is similar to that of peel and appears when a stiff adherend experiences an uneven load. The stress is then larger in one side of the joint. In order to avoid failure from cleavage, a large joint area needs to be applied which can be expensive (Ebnesajjad and Landrock, 2015b, pp. 183–185).



**Figure 2.5:** The five different kinds of stresses that an adhesive bond can experience.

### 2.2.1.1 Thermal stresses affecting adhesive bonds

Coefficient of thermal expansion (CTE) describes the change in size of a material depending on change of temperature within it. The expansion of a material can lead to stresses arising. When combining materials of different CTE it can lead to high levels of stresses in the substrates, as well as in the adhesive layer. Some typical CTE for various adherends and adhesives can be found in table 2.3.

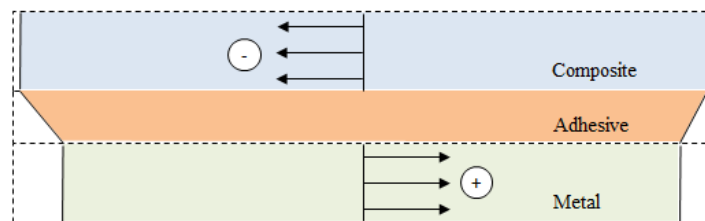
## 2. Theoretical framework

**Table 2.3:** Typical CTE of various adherends and adhesives (E. A. S. Marques et al., 2015)

Material	CTE ( $10^{-6}/^{\circ}C$ )	
Aluminium	24	
Steel	12	
Titanium	9	
Glass fiber	6	
Aramid fiber*	-4	
Carbon fiber (axial)	-0.5	
Carbon fiber (radial)	10	
Carbon fibre reinforced polymer (CFRP) (longitudinal)	-0.1	
Carbon fibre reinforced polymer (CFRP) (transverse)	30	
	Below $T_g$	Above $T_g$
Epoxy	60	180
Bismaleimide	35	114

\*Source for the CTE of aramid fibers (Kim et al., 2012)

When cooling from the curing temperature, or subjected to a temperature cycle an adhesive bond of dissimilar materials will expand or compress differently, leading to a difference in size. When a metal adherend and a composite adherend are joined with adhesive, the metal will shrink once it is cooled from the curing temperature. Meanwhile the composite, with a lower CTE will not present a significant change in length. The ability to handle the difference in length between the substrates depend on the level of flexibility of the adhesive. For a stiff adhesive, such as epoxy, it is not easily handled and can cause the composite to be in a compressive load, and the metal to be in a tensile load (E. A. S. Marques et al., 2015), figure 2.6.



**Figure 2.6:** Stresses in adhesive bond due to difference in CTE during negative thermal load ( $\Delta T < 0$ )

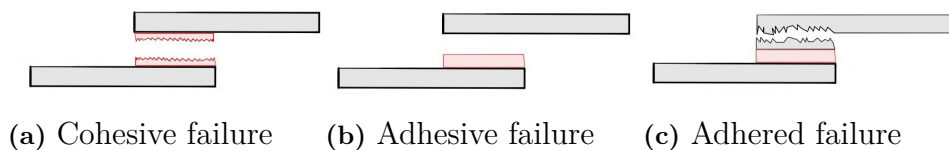
Due to the polymeric nature of adhesives, high-temperature applications have always been a major challenge as their mechanical properties drastically decrease above  $T_g$  and the fact that they degrade or melt at higher temperatures. Constant high temperatures can cause damage to adhesive bonds, but cyclic temperature changes can be even more detrimental as they can introduce cracks and premature failure due to the mismatch in CTE (E. A. S. Marques et al., 2015).

In the article, *Residual Stress Development in adhesive bonds Subjected to Thermal Cycling* by Jr. and Dillard, 1998, The effect of thermal cycling on the residual

stress in polymeric materials bonded to stiff substrates was studied. There is a CTE mismatch between the substrates which induces in-plane strains and stresses in the layers while subjected to temperature cycling. These stresses then result in concentrations of shear- and peel stresses near the edges. The article investigates two different thermal profiles, one in the form of a sine-wave and the other square-wave, because, *"cooling polymers more slowly will result in reduced residual stress levels; as the system cools and residual stresses begin to develop, there is more time for relaxation at the accelerated rates of the higher temperatures. The same principle should apply for thermal cycling. A thermal profile with rapid temperature changes would ultimately induce higher residual stresses more quickly than a profile with lower changes"* (Jr. and Dillard, 1998, p. 294). The stresses in the sine-wave was predicted to be about 2.5% lower than for the square-wave. In both thermal profiles the residual stress increase with each number of cycle, but over time the stress in the adhesive layer asymptotically levels off into a steady-state stress value. The number of cycles needed to reach steady-state depends on polymer properties, thermal history and the cycling environment, and is hard to predict. Diagrams in the article shows a big difference between 1 cycle to 10 cycles in shear stress distribution (Jr. and Dillard, 1998, p. 299), while the difference between 10 cycles to 100 cycles are not as distinct.

### 2.2.2 Adhesive failures

Adhesive failures can occur in a multitude of different ways but can be divided into two main categories, adhesive- and cohesive failure. Adhesive failure occurs between one of the adherends and the adhesive, figure 2.7b. It is usually caused due to weakness in the boundary layer and the reason is most of the time because of improper surface preparation. For cohesive failure, figure 2.7a, parts of the adhesive can be found on both adherends after failure. Failure could also come in the form of complete failure in one of the adherends, figure 2.7c, which is called adherend failure and is rather rare (Messler, 2011, pp. 195–197).



**Figure 2.7:** Adhesive failures types

Failure for one of the adherends or within the adhesive is seen as the optimal type of failure, when evaluating adhesives. In these cases, the ultimate strength for the materials that are involved in the bond are reached and there is no doubt that there are any issues with the bond preparation or the procedure of the bonding (Messler, 2011, p. 195).

In most cases, the failure of a bond is neither solely adhesive or cohesive, it is rather a mixture of both. Because of this, the failure mode is described as the amount of

adhesive and cohesive failure. The performance of a bond can however not be purely based on the mode of failure. For example, adhesive failure could occur for some combinations of adhesives and adherends at higher strengths than a similar bond that fails cohesively with a weaker adhesive. So even though the failure mode is of interest when looking at adhesive bonds, it is ultimately the maximum strength of a bond that is most important (Messler, 2011, pp. 195–196).

### 2.2.3 Adhesive bond design

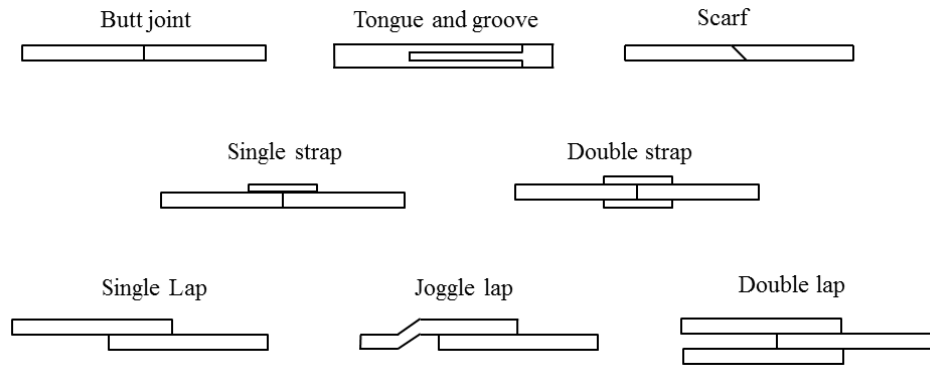
The area of the adhesive bond must be large enough so that it can endure the maximum force when in use. For a single-lap bond, the stress is the highest at the ends of the lap and the center of the bond carries a relatively low amount of stress. Therefore, if the length of the bond is increased, it will lead to a rather low gain in strength. By increasing the width of the bond it is possible to obtain a higher amount of strength (Ebnesajjad and Landrock, 2015b, p. 188).

The optimum adhesive bond should be stressed in the direction where it has the highest resistance against failure. There are a wide range of different types of adhesive bonds with varying levels of strength. Some of these can be seen in figure 2.8 (Ebnesajjad and Landrock, 2015b, p. 189).

Butt joints are one of the more simple types of adhesive bonds. This type of bond is not suitable for applications where bending forces could occur, due to cleavage stress. Butt joints do not work well with thick adhesives but can be modified in different ways in order to still be suitable for those applications. Tongue and groove joints and Scarf butt joints are some variations of butt joints that could improve its strength for those cases (Ebnesajjad and Landrock, 2015b, pp. 189–190).

Strap joints keep forces aligned and are typically used for applications where a thick adhesive bond is required. In similar manner as the butt joint, they experience cleavage when bending forces are applied. The double strap joint are superior in resisting failure when experiencing bending (Ebnesajjad and Landrock, 2015b, p. 191).

Lap joints are the most common adhesive bond. They are easy to produce and are compatible with thin adherends. Furthermore, they stress the joint in shear, which is usually the strongest direction of the adhesive bond. However, for a regular lap joint the shear forces are not in line due to the adherends being at an offset relative to each other. The joint could therefore be improved by redesigning it so that the load on the adherends are in line. The easiest method to bring it in line is to bend the adherends, this is called a joggle lap joint. Double lap joints could be another method to create a balanced construction. However, it will experience bending if the double side is not subjected to the same amount of load (Ebnesajjad and Landrock, 2015b, pp. 190–191).



**Figure 2.8:** Types of adhesive bonds that are commonly used for different applications.

**The thickness of an adhesive bond** affects the final strength of an adhesive bond. It has been shown that a thinner bond line increases the strength of a lap-joint and the maximum strength was found for bond lines between  $0.05\text{-}0.5\text{ mm}$ . However, this range can not be applied to all cases as other factors influence the strength, like load type, behaviour of the adherend and the type of adhesive. When flexible adhesives are used, for a peel joint, a thicker bond line is sought after because the load can be distributed over a larger area (da Silva et al., 2017, p. 1092).

#### 2.2.4 Mixed adhesive joints

A common issue for composite materials are their sensitivity towards transverse loads, which can lead to delamination and adherend failure. If this is not kept in mind when designing the bond, large peel stresses can occur at the ends of the bonded area. One way to combat this is to use a flexible adhesive that can distribute the stresses throughout the bond and reduce stress concentrations in certain areas. However, the bond strength of flexible adhesives can be rather low and not suitable for structural applications. In order to avoid delamination and adherend failure while still keeping a high bond strength, mixed adhesive joints could be a solution. This type of bond utilizes a flexible adhesive at the edges of the bond, to avoid peeling, while having a stiff adhesive at the center of the bond to contribute to the strength (Machado, E. Marques, and Silva, 2018, pp. 68–69).

A study has been done on bonding CFRP to CFRP with mixed adhesive joints. They looked at the behavior of the bond under quasi-static loads, load that is applied slowly which leads to very slow strain rate, and impact loads, and how temperature affected the results. The low temperature was set to  $-30^{\circ}\text{C}$  and the high temperature was determined to be  $+80^{\circ}\text{C}$ . It was then compared to joints that only consisted of the flexible or the stiff adhesive. It was found that the mixed adhesive joint improved the failure load at room temperature (RT) and was similar to that of the stiff adhesive while at low temperatures. However, it performed poorly at high temperatures due to the temperature being more than the  $T_g$  of the flexible adhesive. It was determined that the mixed adhesive joint was only suitable when

used in RT due to the limitations of the adhesives at low and high temperatures. When looking at impact conditions, the mixed adhesive joint performed better at RT and high temperatures, while failure by delamination occurred earlier for adhesives with higher stiffness. The reason that the mixed adhesive joint performed well at high temperatures for impact loads and not quasi-static loads was connected to the viscoelasticity at temperatures above  $T_g$  for the flexible adhesive. These results may vary depending on the adhesives being used (Machado, E. Marques, and Silva, 2018, pp. 76–78).

### 2.3 Surface treatments prior to adhesive bonding

There are various methods for surface treatment on the adherend surface to create stronger adhesive bonds. Some of these are grit blasting, abrasion, plasma treatments, acid chemical etching, peel-ply, and laser processing. Blasting and abrasive processes are the most common when it comes to mechanical methods. These methods could cause damage by fracturing the fibers and delamination of the fiber matrix, therefore, it is crucial to perform them with care. Most of the time additional cleaning operations are necessary to remove particles, grease and other contaminants that could occur before and after the surface treatment. (Çoban et al., 2019, pp. 1–2).

#### 2.3.1 Abrasive machining

Using abrasion as a surface treatment is common for composites as a way of removing the gloss from the surface or making it rougher. Different methods of abrasive machining can be categorised based on those that use bonded tools, for example grinding wheels, or methods that use loose abrasives. It is crucial to monitor the process when using the different methods to not make the surface excessively rough. The joint strength could weaken if the surface roughness is too high because of stress concentrations (Rudawska, 2019b, pp. 89–91).

Abrasive blasting is one of the methods that uses loose abrasive media to remove and deform the surface. The properties of the media and the angle that it hits the surface are both important parameters that affect the final result. Blasting methods can be divided depending on if they use water for the medium or not. Dry blasting usually produces a surface finish that is coarser than what can be achieved with hydro-abrasive blasting. The downside with incorporating water is that it may cause corrosion, therefore sodium or sodium nitrite is usually used as a supplement to hinder the corrosion (Rudawska, 2019b, pp. 93–95).

Sandblasting is a method that uses abrasive particles in compressed air or liquid to treat the surface of the component. The material and diameter of the particles can be altered to fulfil the specific roughness that is requested. Sandblasting can be used as surface treatment for steel, titanium alloys, aluminium alloys, polymers or composites before adhesive bonding. The particles are usually made up of silica sand but some other options are metal particles, dry ice particles, crushed glass and glass/ceramic beads (Rudawska, 2019b, pp. 95–97). Sandblasting does not produce

the optimal results when used by itself on aluminium. The initial bond strength is relatively good, but it will degrade under moisture and heat (Campbell, 2011, pp. 246–247).

Grinding is a method that uses an abrasive tool rather than submerging particle in a liquid. It is usually performed with a grinding disc where the grains have different size/shape and are distributed randomly on the disc. The method could also be carried out with a belt grinder, which can create a surface finish that is superior to that of a grinding wheel. The downside is the loss in dimensional accuracy. (Rudawska, 2019b, p. 98)

### 2.3.2 Anodising

Anodising is a surface treatment that creates an oxide coating through an electrochemical method. It is usually used when working with aluminium but also some types of steel, magnesium and titanium (Rudawska, 2019a, p. 149).

The process consists of submerging the metal in an electrolyte together with another element. Electrical current is then lead through the electrolyte which makes the chosen metal an anode and the other element becomes the cathode. This causes an oxide film to form on the anode and simultaneously hydrogen develops on the cathode. The variables that affect the final properties of the coating are the materials that are being treated, the method of the coating formation and the initial surface treatment that is present before the anodising. The amount of porosity on the surface can be regulated by changing the time that it is being anodised, voltage, temperature and concentration of the electrolyte (Rudawska, 2019a, pp. 147–149).

**Phosphoric acid anodizing (PAA)** method was developed in 1975 to create stronger adhesive bonds and avoid failure. This method of surface treatment is commonly used for components made out of aluminium. PAA has a tubular cell structure, similar looking to whiskers or fingers, with a base made up of oxide. The structure is formed in two steps. The first stage is the formation of the pore cell structure, which is a rather fast process. The whiskers are then formed on the base of cells, which occurs slower than the first stage (Wegman and Twisk, 2013, p. 13).

To achieve lasting bond durability, when working with aluminium, a suitable oxide layer needs to be formed. Anodizing can achieve a porous oxide layer which in some cases is specifically made to be used with a certain adhesive. In order to achieve this, grease and the existing oxide layer on the aluminium needs to be removed. The optimal oxide layer, from anodizing, can then be formed. The surface roughness is then on a microscopic scale (Campbell, 2011, pp. 246–247).

Phosphoric acid anodizing (PAA) requires a temperature-controlled tank, which the part can be submerged into. The solution, within the tank, can be heated both externally and internally, as long as the composition of it does not change. Some common materials to use as cathodes are *316-* or *347-stainless steel*. If the process

is done properly, PAA creates a smooth and uniform coating. No scratches, burned areas, breaks or non-anodized areas should be visible. Once the part is rinsed there should be no water breaks on the surface of the part. An important step to keep in mind is that the part should be coated with some form of corrosion protecting primer within *two* hours, after the part has dried (Wegman and Twisk, 2013, pp. 24–26).

**Chromic acid anodizing (CAA)** has been commonly used as surface treatment for aluminium for many years, and mostly used in the flight- and space industry. In the same way as PAA, it is made up of an oxide layer at the base, which the tubular cells are growing on. This structure is then, in general, transformed into trihydrate aluminium oxide by sealing it in hot water. The sealed layer of oxide that is formed is weak, thick and most often not optimal for bonding with adhesives. However, a small amount of chromic acid can be added to the seal water. This creates a sealed anodized surface, which has good bonding properties. By adding the chromic acid, some of the cell structure dissolves and instead leave a thin and strong aluminium oxide which is suitable for adhesive bonding (Wegman and Twisk, 2013, pp. 17–18).

The *European Chemicals Agency* aims for safe use of chemicals in the *EU*. One of their legislations is the *REACH-list*, which works to phase out substances that can cause serious and lasting effects on the health of humans and of environment. These effects can be carcinogenic, mutagen and reproduction-toxic (ECHA, 2020a). Substances used in the CAA are in the *REACH-list* and thereby needs to be phased out.

### 2.3.3 Adhesive Primer

An adhesive primer is most often an adhesive that has been diluted in an organic solvent. By applying it to the surface of the adherend, it is possible to create a dried film with a thickness that is between *0.0015-0.05 mm*. Using this before applying the adhesive, can lead to multiple advantages. The time between surface preparation and applying the adhesive can be quite short and an adhesive primer can help protect the surface from oxidation during this time. Primers can also improve characteristics of the adhesive, such as the resistance towards peel. There are also certain combinations of adhesives and adherends that can create undesirable reactions when combined, which adhesive primers can help to protect against. Lastly, some primers can develop and retain tack at elevated temperatures or room temperatures. Because of this, adherends or adhesive films can be held in place while assembled, which will improve the amount of control that one has during production (Ebnesajjad and Landrock, 2015c, p. 46).

Even though adhesive primers could provide a multitude of benefits, they are still not mandatory when epoxy adhesives are used. In order for the primer to be useful, it has to improve either the physical or mechanical properties of the adhesive bond. There are a few primers which do not improve either but still provide protection for anodized or deoxidized surfaces (Danforth, 1985, pp. 116–117).



# 3

## Method

This master's thesis was an experimental study of adhesive bonds between polymer matrix composite (PMC) to aluminium, at varying temperatures. An extensive literature study was conducted in the first part of the project to ensure adequate knowledge in the subject. Results from the literature study were mainly presented in the *theoretical framework*, chapter 2.

The project proceeded with a scanning of the database, at the Defense & Security Company (DSC), in order to chart which composites and adhesives were used and to what extent. During scanning of the database environmental requirements for different products at the DSC also were obtained. Data obtained from the scanning were used to judge which material combinations are of most usability for the DSC to be evaluated by testing. Production of the test samples and the adhesion process were done externally at *Elitkomposit AB* in *Uddevalla*.

The experimental part in this master's thesis was done by tensile shear tests, similar to *ISO 4587* (ISO, 2003), for the material combinations. The tests were done in different simulated environments and the results were analysed in *Microsoft Excel*.

The master thesis was done at the DSC to ensure good communication between the involved divisions. A weekly update was sent to the examiner to have a continuous dialogue of the ongoing progress.

### 3.1 Literature study

In order to understand the subject of composites and adhesive bonds better, a literature study was conducted. In the early stages of the project, the main focus was put on understanding the basics of the subject better. Once the basics were covered, more effort could be used to study the relevant materials and the mechanical testing with all the parameters that had to be determined. The literature study was therefore an ongoing process through the majority of the thesis.

The literature study was done by reading books and articles on the subject which were mostly found through *EBSCO Information Services*. Through *EBSCO* it was possible to access content from different publishers, like *Springer* and *Elsevier*. The results from the literature study can be found in *theoretical framework* (chapter 2).

Keywords used in the literature study were: *composite, PMC, prepreg, autoclave, adhesive bond, adhesive failures, joint design, mixed adhesive joints, surface treatments, anodizing*

## 3.2 Scanning of DSC database

Scanning of database, at the DSC, were done through their internal database. The scanning included both reading multiple documents, data sheets and manuals. Furthermore, the product designs were studied with *Creo View Express - PTC* in order to understand how they were constructed.

### 3.2.1 Determination of environmental requirements

In order to establish the different requirements for the environments, land, naval and air, internal documents at the DSC were used. The internal documents specified parameters that differentiate these environments. This project only considered the temperature requirements for the environments, according to the delimitations established at the earlier stages, see section 1.3.

Adhesive bonds that are part of products in land systems have to be operational, with full performance, within the climate zones that reach ambient temperatures between max  $+55\text{ }^{\circ}\text{C}$  to  $-40\text{ }^{\circ}\text{C}$ . Naval products have to be operational in the temperature range of  $+48\text{ }^{\circ}\text{C}$  to  $-34\text{ }^{\circ}\text{C}$ . During storage, systems may be subjected to extreme temperatures due to the absence of any temperature control. Depending on the type of storage, the combination of solar radiation and ambient temperature can cause increased temperatures as high as  $+71\text{ }^{\circ}\text{C}$ . Negative storage temperatures can go down to  $-46\text{ }^{\circ}\text{C}$ . Naval systems have storage temperature in the range from  $+69\text{ }^{\circ}\text{C}$  to  $-34\text{ }^{\circ}\text{C}$ .

The temperatures to simulate the air environment are set from a specific application. The operational temperature for this application ranges from  $-55\text{ }^{\circ}\text{C}$  to  $+100\text{ }^{\circ}\text{C}$ . The product needs to handle a temperature rise to  $+135\text{ }^{\circ}\text{C}$  for *30 seconds* (Aksöz Markos, 2020, Private communication). All temperature requirements are summarized in table 3.1.

**Table 3.1:** Temperature ranges for sea, land and air

	Operational temperature [ $^{\circ}\text{C}$ ]		Storage temperature [ $^{\circ}\text{C}$ ]	
	Max	Min	Max	Min
Land systems	+55	-40	+71	-46
Naval systems	+48	-34	+69	-34
Air application	+100	-55		
Air application, 30 sec	+135			

### 3.2.2 Requirements for the adherends

The collection of data was done through DSC's internal system, where it was possible to find most of the products, their in going components and associated documents. From here, all PMCs and adhesives could be located and then mapped in *Microsoft Excel*. Because the aim was to replace the mechanical joints to adhesive bonds, the materials that the PMCs were attached to were also mapped. Once all the combinations were found, they were analyzed to find the most common material combination as well as where an adhesive bond seemed most suitable to replace a mechanical joint. The aspect that determined if an PMC would be of interest for evaluation by mechanical testing was:

- Can the PMC withstand the determined temperature requirements according to table 3.1?

The dissimilar material that the PMC was adhered to did not have to fulfil the same requirement. It was purely chosen based on which material the PMCs were most commonly joined to in products at the DSC.

By looking at different drawings and 3D-models in the DSC's internal system and *Creo View*, it was possible to find the materials that the PMCs were joined with. The majority of materials had data sheets from the manufacturer and/or internal material specifications at the DSC, with additional information about the properties. By using this information, it was possible to eliminate materials and combinations that were not suitable for adhesive bonding. The most common combination of a PMC joined to another material could then be determined. Evaluating this combination, by mechanical testing, would be considered of most usability for the DSC.

**Additional requirements for selecting the adherends** were considered quite far into the scanning of the adherends. The complexity of the products took the project to a choice of what to focus on. To focus on the properties of the prepreg at the surface, or of the prepreg in the bulk layers.

Many of the sandwich structure's laminates, located at the DSC, are built up of multiple layers of one type of prepreg in the bulk, and one layer of another prepreg at the surface. The reason for a different surface prepreg is usually because it acts as a sacrificial layer or as environmental protection. A sacrificial layer can be processed after curing and works as a buffer for dimensional inaccuracy's that could occur. The difference in properties between bulk and surface prepreg varies. Some properties could be to protect against environmental impact, ability to easier be machined or a cheaper prepreg to fill out the gap needed for the construction. A question that arise from this were: *Which properties are the most important for this master thesis, the properties of the surface-prepreg, or the properties of the bulk-prepreg?*

First it seemed reasonable to focus on the material that acts as a surface layer, because that is the material that the adhesive will be applied on, and determines

the adhesion ability. On the other hand, the thermal loads that the bonds are exposed to makes the materials expand and that expansion is determined by the bulk material. As the main challenge for this master's thesis is the bonding of dissimilar materials, consequently, with different CTE, the expansion of the bulk prepreg is more important. This new shift of focus added requirements when selecting the adherends:

- Can the PMC be used for structural applications?
- Is the PMC used as an bulk prepreg in the composites structure?

### 3.2.2.1 Selecting the adherends

The composites that were found during the scanning of the database are presented in table 3.2. The ones that passed the requirements where then further evaluated, in order to find the most suitable composite for the mechanical testing.

**Table 3.2:** The following were all the prepreps found at the DSC during the scanning of the database. The prepreps that passed all the requirements are marked with a check mark, ✓, and were further considered for the mechanical tests.

Name	Type of reinforcement fiber	Suitable for structural applications	Used as bulk material	T <sub>g</sub> matrix (°C)	Passed requirements
CFRP 1	Carbon	Yes	Yes	200 (Dry), 154 (Wet)	✓
CFRP 2	Carbon	Yes	No	157	
AFRP 1	Aramid	No	Yes	157	
GFRP 1	Glass	Yes	No	157	
GFRP 2	Glass	Yes	Yes	110-120	✓
GFRP 3	Glass	No	Yes	110-120	
GFRP 4	Glass	Yes	No	180-200	
GFRP 5	Glass	Yes	Yes	125	✓
AFRP 2	Aramid	Yes	Yes	180-200	✓

CFRP is not commonly used in many products at the DSC, as well as not suitable for transmission of microwaves. Therefore it would not be useful as adherend to use for the mechanical tests. For that reason, it was not further considered as an alternative. Both GFRPs that passed the requirements, seemed as suitable options. However, *GFRP 5* is going to be substituted by an equivalent GFRP, but this is ongoing process. *GFRP 2* is thereby the only GFRP left that passed all the requirements and is used for products.

Just as for the aerospace industry, the DSC uses the Material Operational Limit (MOL) by subtracting  $28^{\circ}\text{C}$  from the T<sub>g</sub>. The chosen GFRP should therefore not be used for the flight application where  $100^{\circ}\text{C}$  is set as the requirement, as the T<sub>g</sub> with the MOL reduction falls under this requirement. In order to still be able to cover the air applications, *AFRP 2* will also be evaluated when adhesively bonded at elevated temperatures.

The most common dissimilar material was *aluminium 6082-T6* and this alloy will therefore be adhered to both *GFRP 2* and *AFRP 2*. Using dissimilar materials for an adhesive bond could result in a weaker bond than when the adherends are of the same material, due to mismatch of CTE. For this reason, an adhesive bond between *GFRP 2* and *GFRP 2* will be evaluated, by mechanical testing, in order to obtain a reference that the dissimilar bond can be compared to.

**GFRP 2** is a glass fiber epoxy prepreg. The epoxy matrix systems has a curing range from  $80-135^{\circ}\text{C}$ ,  $T_g$  at  $110-120^{\circ}\text{C}$  and is suitable for structural applications. The fiber system in this prepreg is a stitched  $\pm 45^{\circ}$  biaxial weave of E-glass fiber. The prepreg has 49% fiber volume and a mass per unit area at  $800\text{ g/m}^2$ . The Poisson's ratio is 0.16, with a E-modulus of  $19.4\text{ MPa}$  and a CTE of  $16.77-17.84\ 10^{-6}/^{\circ}\text{C}$ , depending on direction. The layer thickness is  $0.614\text{ mm}$ . The data available for this prepreg is found in internal documents at the DSC.

**AFRP 2** is the prepreg that will be used for the high-temperature mechanical test, representing air environment. It is a 4 harness satin weave with a mass per unit area of around  $315\text{ g/m}^2$ . The matrix is made up of epoxy and constitutes 46 weight% of the prepreg. The curing temperature of the material is  $+180^{\circ}\text{C}$ . The E-modulus evaluated in bending is between  $22-28\text{ GPa}$ .

**Aluminium 6082-T6** is a wrought aluminum alloy. Beside aluminium, the largest constituents of elements present in the alloy are silicon and manganese. It has medium strength and great resistance against corrosion. It has a density of  $2700\text{ kg/m}^3$  and a E-modulus of  $70\text{ GPa}$ . CTE for *aluminium 6082-T6* is  $24 \times 10^{-6}/^{\circ}\text{C}$ . The weldability is excellent but the strength decreases in the heat affected zone. The machinability is good as well. Some common applications are for bridges, cranes and transport applications (AZoM, 2005).

### 3.2.3 Requirements for the adhesives

The selection of the adhesive started with mapping of structural adhesives from different manufacturers. There was also a document, at the DSC, with available adhesives at the company. Choosing an adhesive that was already available would be beneficial, because introducing a new material could be a lengthy process. However, there would still be a possibility to choose a new adhesive, depending on when in the project the selection of the adhesive was done, and the lead time of the specific adhesive. An *Microsoft Excel* sheet was created to document the adhesives that could be used for the mechanical tests. The document was categorised based on the application and properties of the different adhesives. In order to avoid complications regarding the thickness and uniformity of the bond, an adhesive in the form of an adhesive film was chosen. The requirement that the adhesive film had to fulfil were:

- Have a minimum service temperature of  $-55^{\circ}\text{C}$  or less and a maximum of at least  $+135^{\circ}\text{C}$ , these temperature requirements can be found in table 3.1.
- Have a curing temperature that is less than the  $T_g$  of the matrix.

- Be suitable for structural applications.

Once the adhesive films that did not fulfil the requirements were eliminated, it was possible to select which one to use for the mechanical tests. This was based on their shear strength, which was most commonly tested by the manufacturers according to the standard *ASTM D1002* (ASTM International, 2019). *ASTM D1002* is exclusively used for adhesive bonds between metals and was therefore only seen as a reference value to predict the strength of the adhesive films. The adhesive film that fulfilled all the requirements and had the highest strength was evaluated by mechanical testing.

#### 3.2.3.1 Selecting the adhesive film

Table 3.3 shows the first scanning of possible adhesives for the testing of the adhesive bond. The ones that passed all the requirement are marked with a check mark, ✓, in table 3.3.

**Table 3.3:** The following table presents the thermal properties of *FM 73* (Solvay, 2017b), *FM 300* (Solvay, 2018) and *FM 300-2M* (Solvay, 2017a).

Adhesive	Cure temp.	Service temp. min	Service temp. max	Passed
FM 73 (300 gsm)	121°C	-55°C	+82°C	
FM 73 M (300 gsm)	121°C	-55°C	+82°C	
FM 73 OST (300 gsm)	121°C	-55°C	+82°C	
FM 300M (146 gsm)	177°C	-55°C	+149°C	
FM 300M (391 gsm)	177°C	-55°C	+149°C	
FM 300-2M (146 gsm)	121°C	-55°C	+149°C	✓
FM 300-2M (244 gsm)	121°C	-55°C	+149°C	✓
FM 300K (146 gsm)	177°C	-55°C	+149°C	
FM 300K (391 gsm)	177°C	-55°C	+149°C	
FM 300-2K (391 gsm)	121°C	-55°C	+149°C	✓
FM 300-2K (489 gsm)	121°C	-55°C	+149°C	✓

The adhesive films that passed all the requirements were then evaluated based on their shear strength. The adherends for the tests in the datasheets were aluminium to aluminium, according to the standard *ASTM D1002* (ASTM International, 2019). The table with the shear strength at different temperatures can be found in table 3.4

Out of these alternatives, *FM 300-2M (244 gsm)* and *FM 300-2K (489 gsm)*, did not have recorded values at  $+149^{\circ}C$ . Because of the uncertainties regarding the strength of the adhesives at  $+135^{\circ}C$  and above, these two adhesives were not chosen for the tests. *FM 300-2M (146 gsm)* had the highest strength at elevated temperatures and is already available at the DSC. It does not have recorded strength for  $+24^{\circ}C$  and  $+82^{\circ}C$ , but these would most likely be greater than that of  $+121^{\circ}C$  and therefore strong enough. Because of these reasons *FM 300-2M (146 gsm)* seemed like the most suitable adhesive to be used for the mechanical test.

**Table 3.4:** Comparison of shear strength for the adhesive films that passed all the requirements. The values for shear strength were done according to *ASTM D1002* (Solvay, 2017a).

Adhesive	ASTM D1002: Lap Shear (MPa)				
	-55°C	+24°C	+82°C	+121°C	+149°C
FM 300-2M (146 gsm)	27.6	-	-	27.9	20.4
FM 300-2M (244 gsm)	29.8	33.5	35.5	26.2	-
FM 300-2K (391 gsm)	31.6	40.7	36.6	25.7	15.8
FM 300-2K (489 gsm)	29.5	37.3	35.9	25.9	-

### 3.3 Test samples production and preparation

This section describes the dimensions, surface treatment and manufacturing process of the test samples. Production and the adhesion process of the test samples were done externally by *Elitkomposit AB*. A report over their entire process can be found in the appendix A.

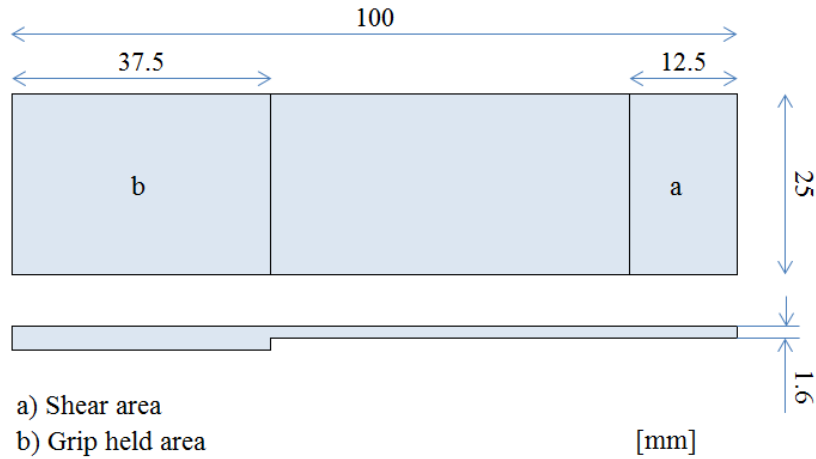
#### 3.3.1 Test sample dimensions

The dimensions of the test samples were done similar to *ISO 4587*, with extra thickness in the form of a tab at the grip held area, see figure 3.1. Before this master's thesis, previous experiments have been conducted at the DSC, where there were complications with lack of grip in the tensile shear testing machine. Experience from the DSC has shown that this can be avoided by increasing the thickness of the grip held area of the test samples. For more exact tolerances see *ISO 4587* (ISO, 2003). At the shear area, see **a**) in figure 3.1, the adhesive film will be applied for bonding another test sample, either one in same material, or of a dissimilar. Adherends are the pieces that will be adhesively bonded together while the test sample is considered to be the complete specimen with adherends and adhesive included.

The *aluminium 6082-T6* test samples were manufactured according to figure 3.1 and tolerances from *ISO 4587*. Test samples manufactured from the PMC materials, *GFRP 2* and *AFRP 2* were outside the tolerances regarding the thickness set by *ISO 4587*. The PMC test samples deviate because they are built up by several layers of prepregs. The number of layers were adjusted to be close to *ISO 4587*'s thickness value of  $1.6\text{ mm}$ , but the achievable precision was dependent on the prepregs thickness.

The *GFRP 2* prepreg have a thickness of  $0.64\text{ mm}$  each, and the test samples were done with 4 layers, resulting in a thickness of  $2.56\text{ mm}$ . To be closer to the *ISO 4587* thickness of  $1.6\text{ mm}$ , 3 layers could have been used ( $=1.92\text{ mm}$ ), but then the laminate would be unbalanced in the ply-orientation. The fiber-orientation for the GFRP were *0-90-90-0*.

The *AFRP 2* test samples were done in 7 layers, each layer with a thickness of



**Figure 3.1:** Material sample dimensions similar to *ISO 4587*, with extra thickness for the grip held area.

$0.213\text{ mm}$ , resulting in a test sample thickness of  $1.49\text{ mm}$ . The layers were all in the same fiber-orientation.

The tabs at the grip held area for, all the test samples, were done with *GFRP 2*. The tabs were made in the same way as the *GFRP 2* test samples, by 4 layers in  $0-90-90-0$  fiber-orientation. Resulting thickness of the tabs were  $2.56\text{ mm}$ .

### 3.3.2 Curing of PMC laminates

The PMC laminates were both cured in a autoclave process. The *AFRP 2* laminate was cured in  $180^\circ\text{C}$ , and the *GFRP 2* laminates were cured in  $120^\circ\text{C}$ , both curing cycles are described appendix A.

### 3.3.3 Surface treatment of test samples

The shear area of all the test samples were surface-treated by sandblasting prior to the adhesion process.

In the early stages of the project, the idea was to surface-treat the *aluminium 6082-T6* by phosphoric acid anodizing (PAA). PAA has been proven as a good surface treatment prior to adhesive bonding for aluminium, and was also recommended internally at the DSC. Chromic acid anodizing (CAA) was not selected due to it being phased out for health and environmental reasons. For the PAA, another subcontractor had to be involved in the project. With a limited time frame, the decision was to not risk delaying the project, and thereby not to perform PAA. By surface-treating the *aluminium 6082-T6* adherends with sandblasting it could be performed at *Elitkomposit AB*, and therefore lowering the risk of delays.

Using a primer for the adhesive process was considered, but in the end it was not selected. The primer of interest, *BR 127* (Solvay, 2020), contains substances that are



both carcinogenic and suspected to be mutagenic, e.g. *formaldehyd* (ECHA, 2020b), and therefore needs to be phased out in the upcoming years. The experimental results obtained while using primer *BR 127* would therefore only be valid for a limited period of time, as the primer will be phased out. There is currently a search for a suitable replacement but no other options have been found at the DSC, as of the time of this project. As one of the delimitations was to only use materials that are available at the DSC, as well as the time frame being too narrow, no primer was used for the test samples.

### 3.3.4 Adhesion process

After surface treatment the test samples were cleaned with water, and then dried in  $120^{\circ}\text{C}$  for *70 hours*. Tabs were then glued to the test samples.

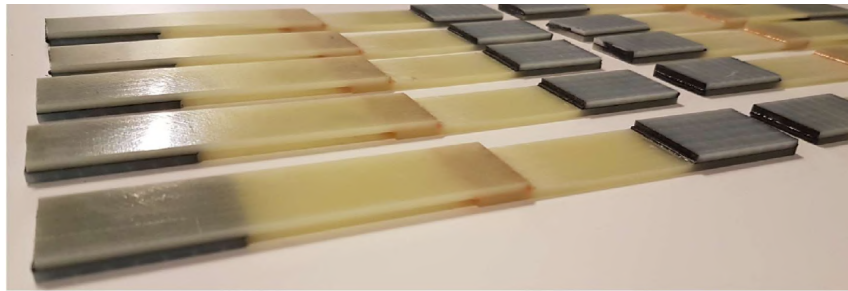
Two layers of *FM 300-2M* were used for the adhesion process between the test samples. Each layer has the thickness of *0.13 mm*, and two layers resulted fairly close to the *ISO 4587* adhesion thickness. Consultation with an expert in the area at the DSC also recommended two layers of the adhesive film (Petersson, 2020, Private communication). The adhesive film was cured with an increase of  $1.6^{\circ}\text{C}/\text{minute}$  up to  $121^{\circ}\text{C}$ , with a pressure of *0.28 MPa* for *90 minutes*.

After the adhesion process the test samples were cut by water jet to dimension according to *ISO 4587*, thus  $187.5 \times 25 \text{ mm}$ . In figure 3.2 test samples after production and adhesion process can be seen. More figures can be found in appendix A.

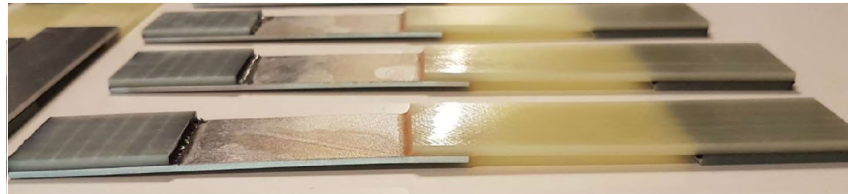
## 3.4 Equipment and parameters for mechanical testing

Evaluating adhesive bonds by testing can be done in several different ways. For finding which method to use for this master's thesis *ISO*, *ASTM* and internal standards were considered and compared.

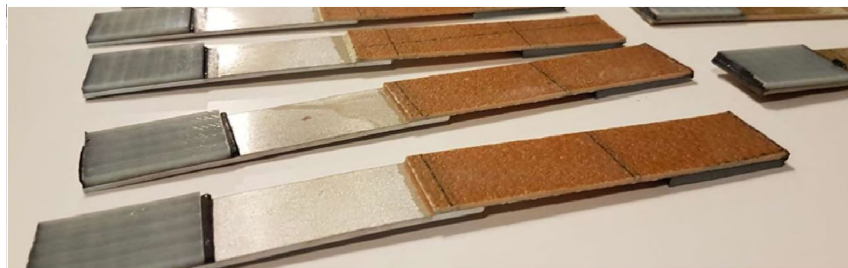
The standard, *ASTM D1002* (ASTM International, 2019), is only applicable for metal adherends and was therefore excluded. Even though most adhesive data-sheets used this standard in order to determine the shear strength of an adhesive. To acquire reproducible results, and results that could be challenged, the objective was to not use internal DSC-standards. These documents could limit the understanding of the method, due to confidential matters. These things considered, the choice was to conduct the test according to *ISO 4587: Adhesives - Determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies* (ISO, 2003)



(a) *GFRP 2* adhered to *GFRP 2*



(b) *GFRP 2* adhered to *aluminium 6082-T6*



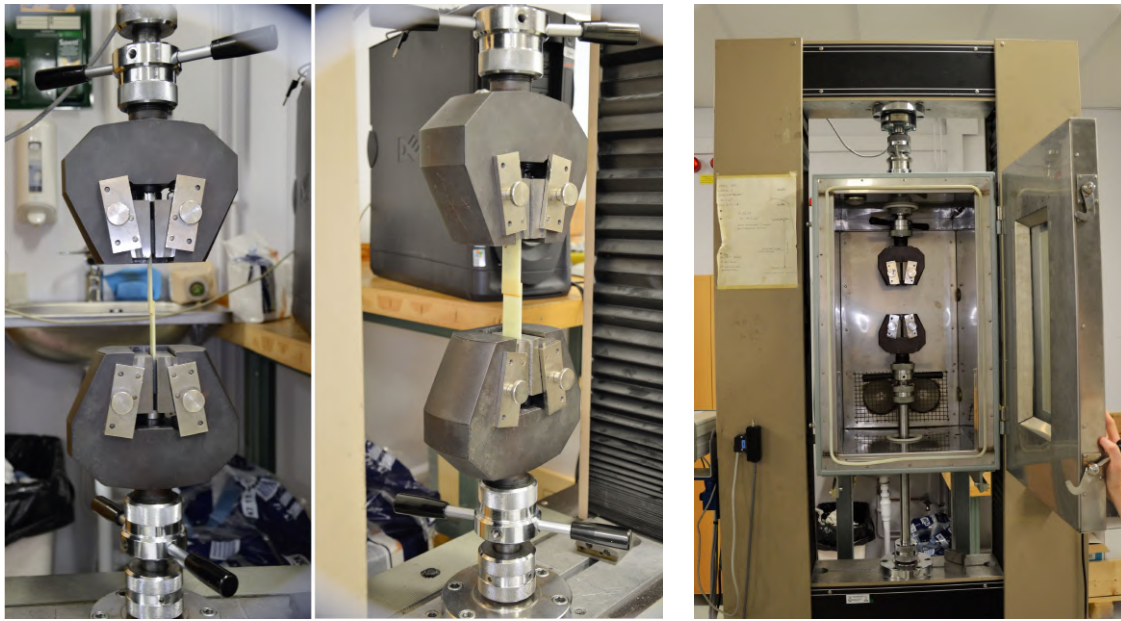
(c) *AFRP 2* adhered to *aluminium 6082-T6*

**Figure 3.2:** Test series adhesively bonded by adhesive film *FM 300-2M*

#### 3.4.1 Equipment used for pre-conditioning and tensile shear testing

The tensile testing machine at the DSC, and the machine used for the tests, was *Alwetron TCT 50* from *Instrument & Calibration Sweden AB*. It is constructed to perform tensile- and compression tests on different shapes and sizes. The test samples are fixed at each grip during testing. The grips are designed with a wedge to ensure increasing clamp force if the cross-section decreases, or if test samples are sliding.

For the test series at elevated temperatures, a compatible temperature chamber with *Alwetron TCT 50* was used. The clamps were replaced with a smaller pair in order to fit in the temperature chamber, see figure 3.3b for instrument setup.



(a) Room temperature setup for GFRP adhered to GFRP

(b) Compatible temperature chamber installed for elevated temperature testing

**Figure 3.3:** Tensile shear test setup in *Alwetron TCT 50*

In order to ensure that the test samples had the desired temperature during the tensile shear testing, an oven was used for pre-heating. The oven used was *Vötsch VT 4002*, where all five test samples of a series could be pre-heated at once. The test series that would require temperature cycling, the climatic chamber *Vötsch VCS 7048-15* was used. Together with the program, *SimPati 2016*, the desired temperature cycles could be implemented with the desired temperature change rate, max/min temperature and temperature plateaus.

### 3.4.2 Ambient test temperatures and pre-cycling temperature intervals

For land and naval systems, the most extreme environments were the storage temperatures, which ranged from  $-46^{\circ}\text{C}$  to  $+71^{\circ}\text{C}$ , and  $-34^{\circ}\text{C}$  to  $+69^{\circ}\text{C}$  respectively, see table 3.1. The temperature requirements are quite similar for land and naval, hence it was determined to simulate them with the same temperature intervals. The number of test series could therefore be reduced. The temperature interval that simulated land and naval environments thereby were  $-46^{\circ}\text{C}$  to  $+71^{\circ}\text{C}$ . The temperature interval to simulate the environment for air applications were  $-55^{\circ}\text{C}$  to  $+100^{\circ}\text{C}$ , and  $+135^{\circ}\text{C}$  for *30 seconds* (Aksöz Markos, 2020, Private communication).

Polymers do not degrade at low temperatures, which they do when exposed to elevated temperatures. Therefore, the adhesive bond was not tested in the lowest ambient temperature for the respective interval. Each material combination was tested in their respective maximum ambient temperature. For land and sea, the

maximum ambient test temperature was  $+71^{\circ}\text{C}$ . For air environment this test temperature was  $+100^{\circ}\text{C}$ . The maximum temperature at  $+135^{\circ}\text{C}$  was only used for the pre-cycling for the air environment, and not used as ambient maximum test temperature due to its short duration.

The evaluation of how the mismatch of CTE affects the adhesive bond strength was conducted by pre-cycling the test samples when adhesively bonded. For these test series, the temperature interval for each environment was used to evaluate how temperature cycling affects the adhesive bond. As previously mentioned in the *theoretical framework*, see section 2.2.1.1, there is the most difference in residual stress between 1 and 10 temperature cycles. The differences after that is not as noticeable (Jr. and Dillard, 1998). Due to uncertainties regarding how many cycles the material combinations of this project requires to reach steady-state, 10 cycles were determined to be a sufficient number, and reasonable within the time frame.

### 3.5 Implementation of shear tests and pre-cycling

In this section the process of the tensile shear testing are presented, including how the test series are planned and how the testing is implemented and later on analysed.

#### 3.5.1 Test matrix

One test series contained *five* samples of the same combination of adherends and same environmental conditions, such as ambient test temperature and pre-cycling. The matrix for the test can be seen in table 3.5. Each **x** in the test matrix represents one test series for that material combination and for the specified temperature condition. All material combinations were tested in RT to obtain a reference value. RT was determined to be  $+23^{\circ}\text{C}$  for the test series in this thesis. For calibration, left-over pieces from the production were used.

The pre-cycling intervals represents the temperature variations for respective environment. Test series subjected to temperature cycling were after the cycling tested in RT. This to determine how the mismatch of CTE affected the bond strength

**Table 3.5:** Test matrix for material combinations and temperature conditions for tensile shear testing

Material combination	Temperature conditions				
	Ambient temperature [ $^{\circ}\text{C}$ ]			Pre-cycling interval [ $^{\circ}\text{C}$ ]	
	RT	+71	+100	-46 $\leftrightarrow$ +71	-55 $\leftrightarrow$ +135
GFRP - GFRP	x			x	
GFRP - Aluminium	x	x		x	
AFRP - Aluminium	x		x		x

### 3.5.2 Temperature pre-cycling

One cycle started at RT, lowered to its minimum ambient temperature, held for *30 minutes*, then raised to its maximum ambient temperature, held for *30 minutes*, and back to RT. The rate was  $5^{\circ}\text{C}/\text{minute}$ . Pre-cycling for the air environment were done in the same way between  $-55^{\circ}\text{C}$  and  $+100^{\circ}\text{C}$ . After  $+100^{\circ}\text{C}$  for *30 minutes* the temperature was intended to be increased to  $+135^{\circ}\text{C}$  as fast as possible. Due to limitations with the climatic chamber it was not possible to reach  $+135^{\circ}\text{C}$  in that rapid rise to the peak temperature. The real temperature in the climatic chamber was around  $+130^{\circ}\text{C}$ , but can unfortunately not be read in figure 3.4b, due to similar curve colors. After reaching the peak the temperature dropped to  $+100^{\circ}\text{C}$  and then the cycle continued as before with a temperature change of  $5^{\circ}\text{C}/\text{minute}$ . These cycles were looped *10* times for respective material combination, resulting in a duration of *18 hours* for the *GFRP 2* adhered to *aluminium 6082-T6*, and *21 hours* for the *AFRP 2* to *aluminium 6082-T6*. See figure 3.4 for the complete temperature cycles. After cycling, the test samples were tested in RT.

### 3.5.3 Tensile shear testing at RT

The tensile shear testing was done similar to *ISO 4587* with a deformation speed of  $2\text{ mm}/\text{minute}$  until the adhesive bond broke. Setup for the the tensile testing see figure 3.3a.

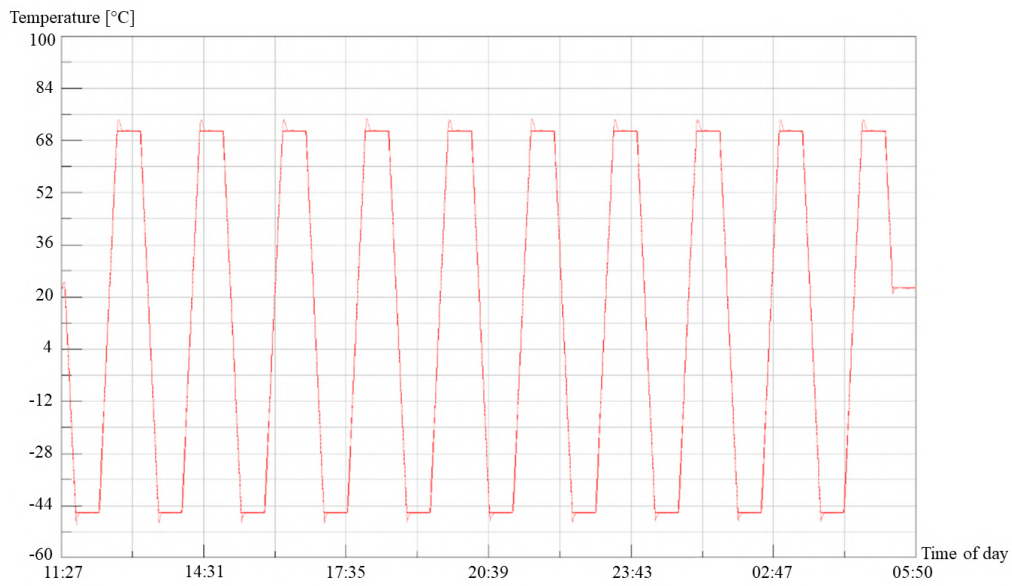
### 3.5.4 Tensile shear testing at elevated temperatures

To enable elevated ambient testing temperatures a temperature chamber was used. figure 3.3b. After installation, it was discovered it was not working properly. It was malfunctioning in controlling and changing the temperature. However, it could still be heated, and used to avoid cooling of the test samples.

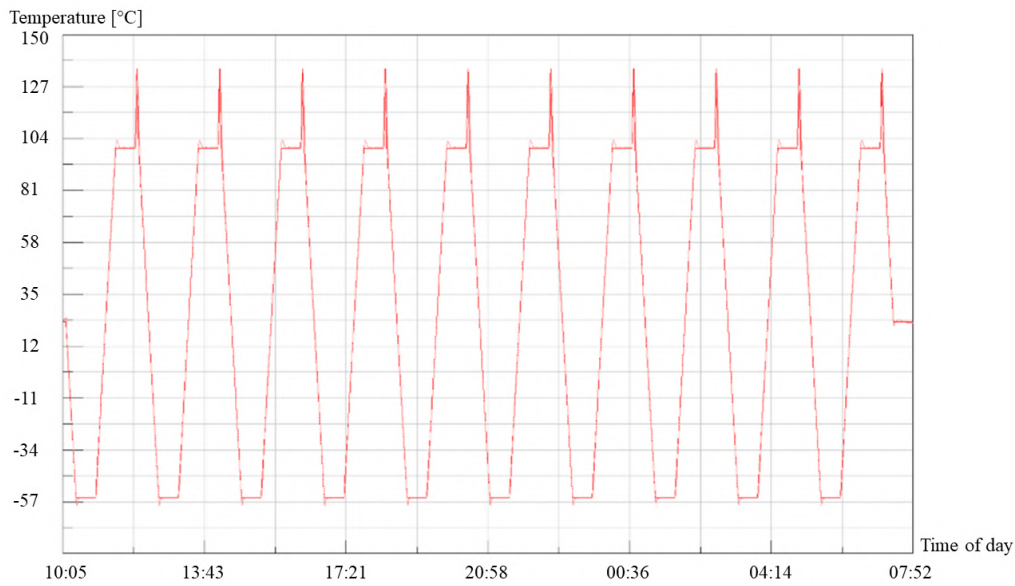
The test series for elevated temperatures were placed in the oven at their respective elevated testing temperature for at least *30 minutes*. When time for testing a temperature sensor was placed on the surface of the test samples, as close as possible to the adhesive bond, to monitor the temperature. The test samples were then moved from the oven to the tensile shear testing machine, that was placed in the temperature chamber. When the samples were put in place, the testing started when the temperature was within  $\pm 6^{\circ}\text{C}$  of respective elevated testing temperature.

### 3. Method

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(a) Temperature cycling for GFRP adhered to aluminium between  $-46^{\circ}\text{C}$  and  $+71^{\circ}\text{C}$



(b) Temperature cycling for AFRP adhered to aluminium between  $-55^{\circ}\text{C}$  and  $+100^{\circ}\text{C}$  with an additional increase to  $+135^{\circ}\text{C}$  for 30 seconds

**Figure 3.4:** Temperature cycling for the dissimilar material combinations

### 3.6 Analysis of data from tensile shear tests

The experiments resulted in a peak force,  $F$ , and displacement where the test sample broke. Each test series consisted of *five* adhesively bonded test samples,  $i=1$  to  $5$ . Shear strength,  $\tau$ , was calculated from the experimental results according to;

$$\tau_i = \frac{F_i}{A_s} \quad (3.1)$$

$A_s = \textit{Shear Area}$

Each test series was represented by the average shear strength  $\tau_{average}$  and a standard deviation,  $\sigma$ . These results were used to evaluate the differences between test series. Standard deviation was calculated according to:

$$\sigma = \sqrt{\frac{\sum(\tau_i - \tau_{average})^2}{n - 1}} \quad (3.2)$$

$n = \textit{number of test samples for each series}$

Analysis of data points from the experiments and calculations were done with *Microsoft Excel*.



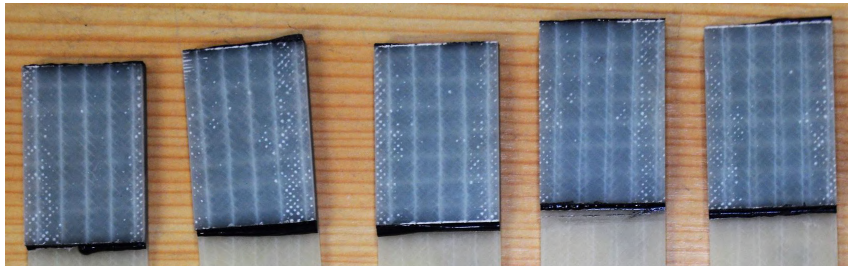


# 4

## Results

The experimental results from the tensile shear testing are presented, and are analysed in this chapter. The course of action can be followed in *Method* (chapter 3). A complete version of the results, including collected force,  $F$ , and displacement from each test series can be found in appendix B. Graphs from the testing summarising each test series force-displacement curve can be seen in appendix C. Shear strength,  $\tau$ , in this chapter was calculated using equation 3.1, and standard deviation,  $\sigma$ , was calculated using equation 3.2. When a result is considered failed and not included in the calculation for tensile shear strength average,  $\tau_{average}$ , and standard deviation,  $\sigma$ , it is struck out in the table, ~~example~~, see table 4.1. A test sample was considered a failure if it behaved as a fractured test sample before the tensile shear testing begun, i.e. if it barely registered any strength during the test. For the sake of simplicity *GFRP 2*, *AFRP 2* and *aluminium 6082-T6* will be called GFRP, AFRP and aluminium respectively.

Not a single test sample has shown any sign of grip sliding during testing. This was controlled by observing the grip held areas after testing. The serrated jaw faces that were attached to the clamps left marks, and if there would have been any sliding the marks would have appeared smeared, but they all looked similar like in figure 4.1, confirming that no sliding had occurred.



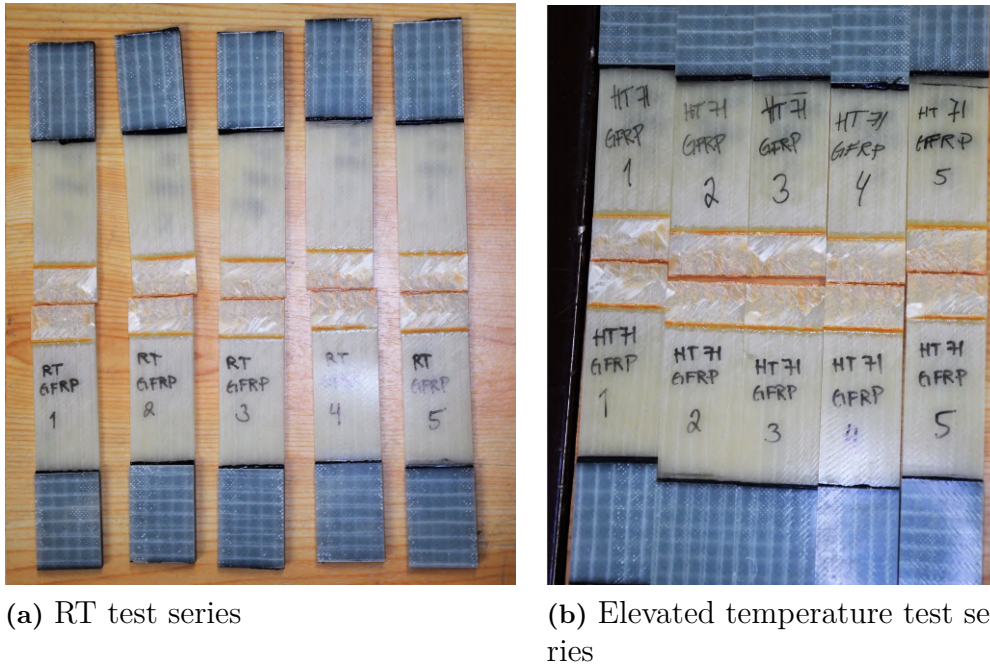
**Figure 4.1:** Grip held area after tensile shear testing, confirming no sliding

### 4.1 Results from GFRP test series

In this section results from all test series including GFRP is presented. To clarify, GFRP adhesively bonded to GFRP, and GFRP adhesively bonded with aluminium.

### 4.1.1 GFRP adhered to GFRP

The test samples for GFRP bonded with GFRP all had failed cohesively as there were adhesive film on both sides of the shear area. For analysing an adhesive bond this result is promising as it indicates that the adhesive film had adhered properly to the surface. See figure 4.2 for all fracture surfaces for GFRP adhered to GFRP.



**Figure 4.2:** Test series of GFRP adhered to GFRP fracture surfaces

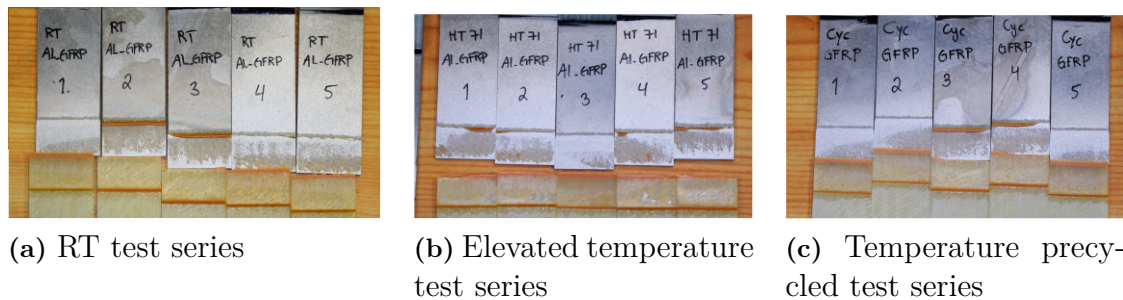
In table 4.1 all calculated results from tensile shear testing for GFRP adhered to GFRP are presented. *Test sample 1* for the high-temperature testing was tested at around  $+50^{\circ}\text{C}$  instead of the desired temperature of  $+71^{\circ}\text{C}$  as only the oven was used without the temperature chamber. Due to this, the sample had time to cool down from the desired temperature. Therefore, the results for *test sample 1* was not included in the calculations for  $\tau_{average}$  and  $\sigma$ .

**Table 4.1:** Resulting tensile shear strength [MPa] for GFRP to GFRP at RT and high temperature,  $+71^{\circ}\text{C}$

Test sample	RT: GFRP-GFRP	$+71^{\circ}\text{C}$ : GFRP-GFRP
$i$	$\tau_i$	$\tau_i$
1	14.37	16.22
2	15.24	14.32
3	15.37	15.63
4	14.51	14.42
5	14.73	14.77
$\tau_{average}$	14.84	14.78
$\sigma$	0.44	0.60

### 4.1.2 Aluminium adhered to GFRP

For the test series GFRP adhered to aluminium the result were quite varied. All results can be found in table 4.2. Test samples with lower tensile shear strength had a fracture surface that failed mainly adhesivly. There were almost no adhesive film left on the aluminium adherend. This can be seen in figure 4.3 for all three test series for GFRP adhered to aluminium. In figure 4.4, a comparison can be seen between fracture surfaces of a test sample that obtained high tensile shear results and a cohesive failure, and a test sample that got lower tensile shear results and showed adhesive failure.



**Figure 4.3:** GFRP adhered to aluminium fracture surfaces after tensile shear testing.



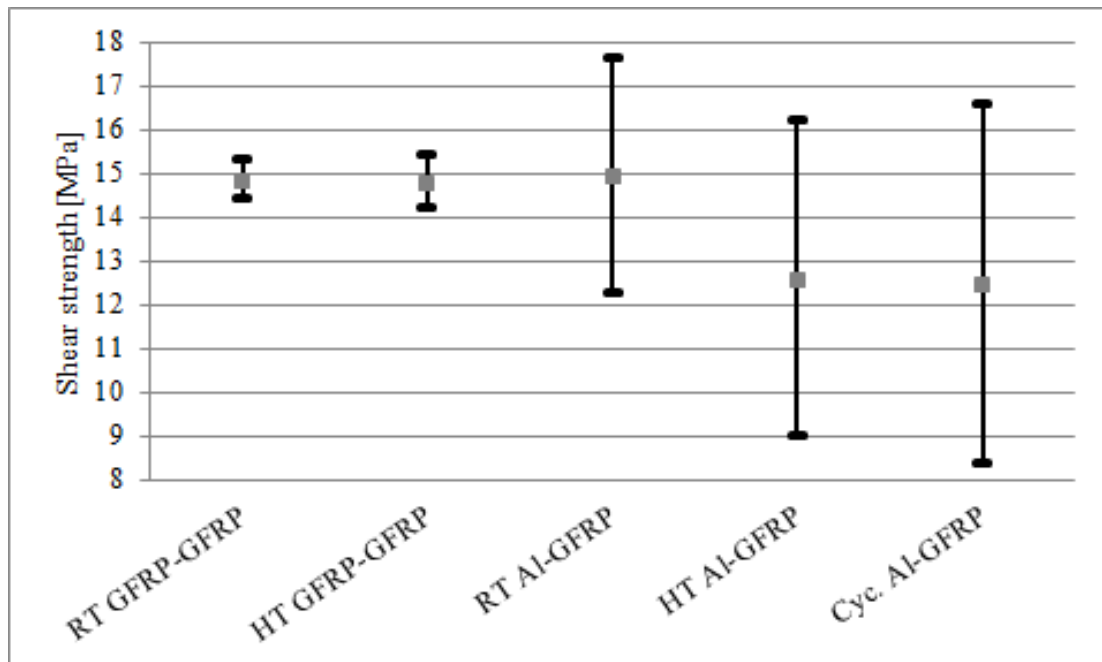
**Figure 4.4:** Comparison between a cohesive and adhesive fracture surface after tensile shear testing between GFRP to aluminium. Left part of figure is test sample 2 at RT testing and shows cohesive failure. Right part of figure is test sample 3 at elevated temperature, shows adhesive failure.

**Table 4.2:** Resulting tensile shear strength [MPa] for GFRP to aluminium at RT, high temperature, +71°C and cycling .

Test sample	RT: GFRP-al	+71°C: GFRP-al	Cycling: GFRP-al
$i$	$\tau_i$	$\tau_i$	$\tau_i$
1	10.52	12.88	8.55
2	17.20	14.86	10.17
3	16.86	6.29	17.37
4	14.52	14.14	16.44
5	15.49	14.68	9.79
$\tau_{average}$	14.92	12.57	12.46
$\sigma$	2.68	3.59	4.11

### 4.1.3 Comparison of GFRP test series

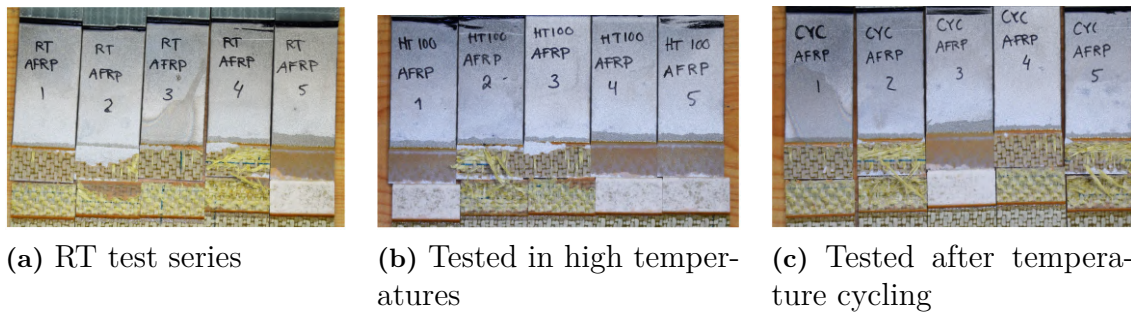
The graph in figure 4.5 is based on  $\tau_{average}$  and  $\sigma$  in table 4.2. The recorded shear strength for all the aluminium to GFRP test samples differed substantially within each test series. This resulted in a large standard deviation and therefore the standard deviation in figure 4.5 is larger compared to GFRP to GFRP.



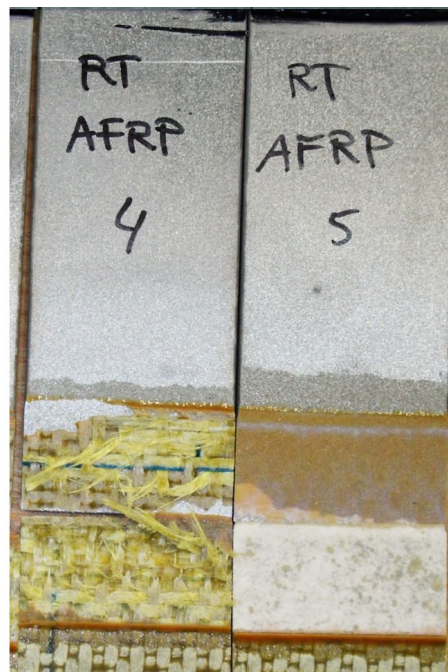
**Figure 4.5:** Comparison between the average value for all the samples containing GFRP. The end of the lines show the maximum and minimum values when the standard deviations are considered. Test series with a smaller line span had similar results in shear strength.

## 4.2 Aluminium adhered to AFRP

Test series for AFRP had issues with early failures, 5/15 test samples were considered failed and were not included in the calculations for  $\tau_{average}$  and  $\sigma$  in table 4.3. All passed test samples showed adhered failure, with remains of the AFRP adhered still attached to the aluminium adhered. The test samples that were considered failed had a white fracture surface. All fracture surfaces can be seen in figure 4.6, and a more closely comparison of fracture surfaces from a passed and failed test sample can be seen in figure 4.7.



**Figure 4.6:** AFRP to aluminium test series after tensile shear fracture.



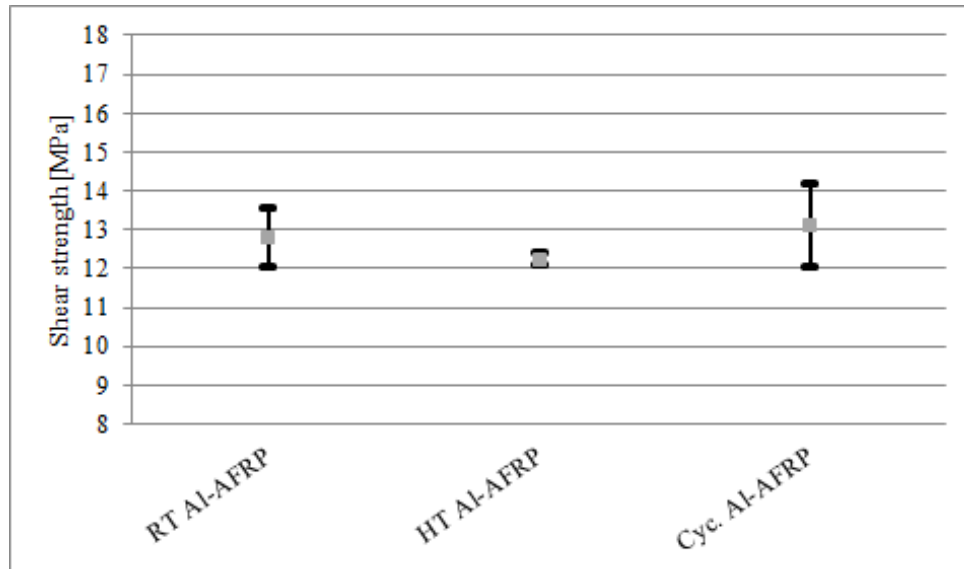
**Figure 4.7:** Comparison between fracture surfaces of a adherend failure and a failed test sample after tensile shear testing between AFRP to aluminium. Left part of figure shows adherend failure in test sample 4 at RT. Right part of figure shows a failed test sample, sample 5 at RT

**Table 4.3:** Resulting tensile shear strength [MPa] for AFRP to aluminium at RT, high temperature, +100°C and cycling.

Test sample $i$	RT: AFRP-al $\tau_i$	+100°C: AFRP-al $\tau_i$	Cycling: AFRP-al $\tau_i$
1	12.07	<del>0.89</del>	13.82
2	12.22	12.34	14.13
3	13.64	12.11	<del>1.31</del>
4	13.21	<del>1.36</del>	12.56
5	<del>1.08</del>	0.64	11.88
$\tau_{average}$	12.79	12.22	13.10
$\sigma$	0.76	0.16	1.06

#### 4.2.1 Comparison of AFRP test series

For aluminium adhered to AFRP, in high-temperatures, *three* test samples were considered a failure and were not included in the average value and standard deviation. Those calculations are only based on the *two* successful test samples and therefore the results from that test series in high-temperatures for AFRP to aluminium are deemed untrustworthy. The test series at RT and cycling each had a test sample that were considered failed and not included in the calculations for  $\tau_{average}$  and  $\sigma$ . Considering this, the results for those test series were similar in strength and standard deviation regardless of temperature and pre-conditioning. The graph in figure 4.8 is based on  $\tau_{average}$  and  $\sigma$  in table 4.3.

**Figure 4.8:** Comparison between the average value for all the samples containing AFRP. The end of the lines show the standard deviations. For aluminium to AFRP at high temperatures the standard deviation was too low to be visible in the graph.

# 5

## Discussion

In this chapter the results are evaluated and discussed. The fracture surfaces and their influence on the resulting shear strength are analysed. The research questions, established at the start of the thesis, are answered and recommendations for future improvements are presented.

### 5.1 Tensile shear tests results

This section of the discussion focuses on analysing the results from the tensile shear testing, and what could have caused the different kinds of failures and shear strength values. The first part focuses on the test series of the GFRP part of the material combination. The second section focuses on the same but as for the AFRP and the third section analyses impacting parameters, as the cycling and the possible bending and twisting of the test samples.

#### 5.1.1 GFRP results

When analysing the results from the test series of GFRP there is a significant difference in  $\tau_{average}$  and  $\sigma$  for the test series of GFRP adhered to GFRP, and GFRP adhered to aluminium. GFRP adhered to GFRP shows a high  $\tau_{average}$  and especially shows a low  $\sigma$ . These results indicate good quality of the surface treatment and the adhesion process. This is proven further by the fracture surfaces, figure 4.2, as all test samples show a cohesive failure. The similar results from the test series tested at RT and at high-temperatures, for GFRP adhered to GFRP, also proves that the adhesive film *FM 300-2M* can carry structural loads at these temperatures for land and naval applications.

Results from GFRP adhered to aluminium have quite high  $\tau_{average}$  values, but the  $\sigma$  values are noticeably higher when compared to the ones at GFRP adhered to GFRP.

Interesting matter, for the GFRP adhered to aluminium test series, is that the highest shear strengths collected are significantly higher than those from GFRP to GFRP. The test samples that show these high shear strength results, like test sample *number 2* and *3* tested in RT, shows more of a cohesive failure than test samples that show lower results and have more of a adhesive failure. An example of this is test sample *number 1* in the same series, see figure 4.3 and table 4.2. A clear compar-

ison between the fracture surfaces of the aluminium adherends can be seen in figure 4.4, but when observing all fracture surfaces in figure 4.3 a connection between the fractured surfaces and their resulting shear strength values, in table 4.2, can be seen.

When bonding GFRP to aluminium the results are not considered reliable as the  $\sigma$  is rather high. The reason for the uneven results is that some samples fail adhesively, assessed to be due to improper surface treatment of the aluminium. The results from the test series tested after cycling, show the lowest  $\tau_{average}$  and highest  $\sigma$ , this can very well be due to the cycling induced stresses that makes de-bonding from the aluminum surface more evident.

### 5.1.2 AFRP results

Analysing values between the test series of AFRP is difficult as the test series in high-temperature can not be utilized as there are only two test samples that were considered successful. Therefore the analyses between the test series are primary between RT and cycling. This combination was prone of failing prior to the tensile shear testing and therefore a test series consisting of more than five test samples would be beneficial.

When comparing the  $\tau_{average}$  of the test series for AFRP adhered to aluminium, against the test series of GFRP adhered to aluminium, it is somewhat lower. But the most interesting aspect is the failure type of the test samples that were considered successful. When observing the fracture surfaces in figure 4.6 and 4.7, an adherend failure can be seen, with left-overs from the AFRP adhered attached to the aluminium adherend. This indicates that it was not the adhesive film that limited the shear strength, but that it was the strength of the AFRP. When observing the fractured adherends, the AFRP looks like it has de-laminated between the prepreg layers. Exactly what has caused this kind of failure is not entirely clear. One possible factor could be that the prepreg layup were unidirectional. By orienting the AFRP prepreg in a different fiber orientations a different kind of failure could have occurred.

Test series of GFRP adhered to GFRP was tested to be a reference value for the test series GFRP adhered to aluminium. The optimal case would have been to have reference test series consisting of AFRP adhered to AFRP as well. Especially as all passed test samples, in AFRP adhered to aluminium, failed adherendly. It would therefore be interesting to see what failure type would be in a test series consisting of AFRP adhered to AFRP. To order more test samples of AFRP was not prioritised due to shortage of material.

Noticeably for these test series is that the adhesion to the aluminium surface does not seem limiting, as it was for the GFRP adhered to aluminium test series. This could be because the passed test samples were all adherend failures. The performance of the adhesion to the aluminium surfaces were not tested and the same goes for the performance of the adhesive film, due to the AFRP adherend failing first for this material combination. There is no distinct difference between the RT test series



and the cycled series. This can either be because the cycling did not effect this combination, or that the adhesive film was affected, but that the AFRP adherend still failed earlier.

### 5.1.3 Possible effects of cycling, bending and twisting

The figures for the comparisons between the test series, see figure 4.5 and 4.8, show that the temperature cycling had minor effect on the strength of adhesives bonds compared to those in RT. There are mainly two reasons for this. The first reason could be differences in CTE for the adherends had much less of an effect on the strength of the adhesive bond than what was initially expected. The second reason is faults within the cycling process. As previously mentioned in section 2.2.1.1, the first 10 cycles shows the biggest impact on the stress value in the material. The value of 10 cycles is more of a general guideline in how many cycles that are enough to reach a steady-state stress, therefore it is debatable if this was enough for the tests in this thesis. An increase in the number of cycles could have lead to a decrease in the bond strength for the test samples.

The failed test samples for the AFRP series all have similar fracture surfaces and low shear stress strengths, see table 4.3. The failed fracture surfaces did not resemble any of the adhesion failures known of. This was interpreted as the adhesive bond had failed prior to the tensile shear testing. The reason that the bond could have failed prior to testing are determined to be either from twisting by the machine, or from bending in the machine.

As for bending, it can be seen in figure 3.2 that the test samples from the different material combinations had different appearances after production. The GFRP adhered to GFRP test samples were straight and did not show any bend. Test series of GFRP adhered to aluminium that can be observed in this figure, 3.2b, show an increase in bending. For the test samples consisting of AFRP adhered to aluminium, figure 3.2c, there is an even larger amount of bending. The bending may have been caused by the mismatch in CTE when the material combinations have been subjected to high temperatures during curing of the adhesive film. This could induce stresses in the bond, and impact the geometry of the test samples. This point of view is strengthened by the non-visible change in geometry for the GFRP adhered to GFRP test samples, figure 3.2a and the low  $\sigma$  from these test series, as matching CTE will not induce these stresses. For the test series of AFRP adhered to aluminium this could have caused the high amount of failed samples as there were stresses in the bond. When fastened in the tensile shear testing machine, the bended shape was created during curing was forced back, and presumably resulting in a failure due to bending in the adhesive bond.

The failed samples could also be explained by twisting of the machine. The machine are supposed to be aligned vertically, thus the clamps should face forward. The tensile testing machine used for this thesis was quite old and the clamps tended to twist when test samples were fastened in it. This problem was more prominent

for testing at high-temperature as other clamps were used, and those twisted a bit more. This could be one explanation to why the high-temperature testing had more failed samples.

The possible occurrence of bending and twisting have not caused any failures for GFRP adhered to aluminium, prior to tensile shear testing, as it did for the AFRP series. But bending or twisting, in the adhesive bond, could be a reason for the early de-bonding from the aluminium surfaces for these test samples.

### 5.2 Additional factors

This section consists of different paragraphs with discussion regarding additional factors influencing the outcome of the mechanical tests.

**The scope** of the thesis was quite broad at the early to mid stages. This led to a extensive database scan as well as having to understand a range of different products at the DSC. This whole processes was time consuming and did not leave much time for experimenting with different bond designs or mixed adhesives joints, which could have given interesting results. Therefore, the limitation of only looking at materials that are already at the DSC seems unavoidable, but could have limit the possibilities of finding a innovative solution. A different approach could have been to focus on a couple of applications where adhesive bonds are of interest. This would have eliminated the majority of the data scanning processes and more research could have been left to create as strong of a bond as possible for that application.

**Humidity** was not considered during this thesis, rather temperature was set as the only changing variable when simulating the different environments. This was determined in order to limit the amount of test samples but also due to time constraints. As the DSC products could operate and be stored in humid environments, tests that simulate aging will be required in order to determine if adhesive bonds can replace mechanical joints. The AFRP could be affected by moisture and would require additional research regarding joint designs and surface treatments in order to minimize the absorption.

The DSC products are exposed to wide range of temperatures that can change at rather fast pace, see chapter 3.4. Temperature was therefore determined as a main threshold that had to be explored in order to further evaluate the adhesive bond. Furthermore, aging simulations can take months which is out of the time frame of this project. The pre-conditioning and testing, that was conducted, in this thesis is most likely not enough to conclude that adhesive bonds can replace mechanical joints. But, analyzing the influence of temperature on the adhesive bond is a base to build further research on.

**The use of surface or bulk** prepregs for the built-up of the test samples for the mechanical testing were considered. As mentioned earlier in the methods chapter,

see section 3.2.2, it was decided to look at the bulk prepregs for the composite build, and thereby to focus on the expansion properties of the prepreg. The optimal case would be to design test samples that are identical to the layer matrix of the product in mind. The layer matrices differ substantially between most composite products at the DSC. Focusing on the specific layer matrix of one application leads to an increased chance of replacing the mechanical joints.

**The ethical aspects** in this master thesis were primarily considered to be; the gain in energy-efficient by using a light-weight material for a fuel-consuming application, weighed against the low level of circularity for PMC materials. The benefits were also weighed against the health risk working with thermosets. A longer and more detailed analysis of the ethical aspects can be found in appendix D.

**Covid-19** has during *spring 2020* developed to a pandemic. This master thesis is relatively unaffected as the DSC has done restrictions, but remained open. Although, some preventive measures have been taken because of the virus. One of these measures was to not use PAA as a surface treatment of the aluminium adherends. This decision was made in order to minimize the risk of delays by involving another subcontractor. To be dependent on subcontractors are always a risk of increasing the lead times, but during *spring 2020*, the risk seemed even higher as many businesses laid off and closed down for a time. Communication and meetings with examiner and supervisor have been challenging due limitations of physical meetings.

**Adhesive primer** was not used for the bonding process, as mentioned previously in section 3.3.3. One of the main benefits of using a primer would have been an improvement in mechanical properties, especially in the resistance against peel. Although, this can not be determined for certain as each combination of adhesive and primer interact differently. Due to PAA not being used as surface treatment for the aluminium adherends, the protection for the anodized surface is not required, which a primer provides. It is therefore difficult to predict how the strength of the adhesive bond would have been affected with a primer included. There were not enough benefits that could be guaranteed in order for it to be justified to use a hazardous material or spend the time to find a suitable new alternative.

### 5.3 Answers to the research questions

*R1:* What are the advantages and limitations by applying an adhesive bond, at varying temperatures, for dissimilar materials?

The 2 chapter covers most of the benefits and limitations of replacing and mechanical joint with an adhesive bond. A summary of the main benefits are: an even stress distribution across the bond rather than concentrating it in the joint, lower weight and does not require any pre-drilling. Some additional insights regarding the replacement of mechanical joints with adhesive bonds were obtained from conduction

the mechanical tests.

Pre-drilling holes in composite components not only damages the load bearing reinforcement fibers but also requires narrow tolerances. Due to the stiffness of the composite structures, small changes in the placement of pre-drilled holes could lead to detrimental results. Furthermore, the dimensions of the composite could be widely different pre- and post curing and therefore the end-product does not always match the intended design. By implementing an adhesive bond, there can be slight changes in dimensions without causing too many issues as the adhesive can adjust according to these differences.

One of the main drawbacks is the necessity to find a suitable surface treatment which can produce bonds of high quality. This adds extra steps in the manufacturing process which requires attention to detail and can be quite time consuming. As seen in the results (chapter 4), all the test series with dissimilar material combination have large deviations between the test samples. This can partly be due to the surface treatment not being the optimal for the chosen combination. So even if the strength for many of those test samples are considered high, the chance of consistently achieving those strengths are low.

The differing curing temperatures between the PMCs and adhesive is another issue that has to be taken into account when creating the bonds. If the curing temperature of the adhesive exceeds the  $T_g$  of the cured PMC part, the matrix could start to degrade. The different CTE of the two adherends and the adhesives could cause residual stresses once the curing of the adhesive is complete. Flexible adhesives can be used to avoid residual stresses, but most structural adhesives are of the stiffer type.

*R2:* Which surface treatment is the optimal for the chosen material combinations, when bonded with an adhesive?

Phosphoric acid anodizing (PAA) was the first choice of surface treatment for the aluminium adherends, as previously mentioned in section 3.3.3. But in the end, sandblasting was selected as surface treatment.

As previously mentioned in section 2.3.1, the initial strength of the two surface treatments, on aluminium, might be similar but exposure to moisture and heat may cause the sandblasted adhesive bond to degrade. This is also noticeable in figure 4.5 where the test series for GFRP adhered to GFRP resulted in a high shear strength with a low standard deviation. On the other hand, the test series for GFRP adhered to aluminium had similar shear strength as GFRP adhered to GFRP but the standard deviation were substantially larger.

It is difficult to predict how this change affected the adhesive bond as multiple variables affect the strength. Some of these variables are: adhesive type, if a primer is used, the types of oxides on the surface and surface roughness. In theory, PAA

seems like the most suitable option for aluminium adherends but it is difficult to draw those conclusions without evaluating it in mechanical tests. In order to determine it with certainty, identical test samples have to be created with surface treatment being the only difference between them.

*R3:* Can the performance of an adhesive bond be sufficient to replace a mechanical joint for chosen material combination?

As this thesis strive to cover a wide range of applications at the DSC, it is difficult to determine any clear shear strengths that have to be reached in order to know if adhesive bonds can replace mechanical joints. As previously mentioned in section 2.2, an adhesive that can be used for structural applications should exceed  $6.9\text{ MPa}$  in single-lap shear strength. All of the test samples in table 4.1, 4.2 and 4.3 that were not considered failures exceeded this limit with exception of *sample 3* between aluminium and GFRP at high-temperature. Even the lowest  $\tau_{average}$  almost doubled the required value to be considered a structural adhesive.

One of the main disadvantages, which indicates that adhesive bonds can not replace mechanical joints, are the large standard deviations that can be observed in figure 4.5 and 4.8. However, this is only true when dissimilar materials were used as adherends. The tests for GFRP adhered to GFRP show promising results as they recorded both a high  $\tau_{average}$  but also a small  $\sigma$ . Replacing a mechanical joint with an adhesive bond between GFRP and aluminium seems possible, as long as the adherends are of the same material.

Even though the strength of the adhesive bonds between the dissimilar materials varied considerably, there were still individual test results recorded for each test series that matched the strength of GFRP adhered to GFRP. Utilizing a different surface treatment and adding an adhesive primer could decrease the standard deviation for these test series. Therefore, even if the average value easily exceeded that of what is required for an adhesive to be considered for structural, the variation in these test series could be decreased with additional research and testing.

## 5.4 Recommendations

- When bonding GFRP to aluminium, the recommendation from this project is to use another surface treatment of the aluminium adherends, preferably phosphoric acid anodizing (PAA) combined with a adhesive primer.
- For further evaluation a test series consisting of AFRP adhered to AFRP should be added in order to obtain reference values for AFRP adhered to aluminium.
- As each test series consisted of *five* test samples it was harmful when one of the samples were considered failed and not included in the calculations for  $\tau_{average}$  and  $\sigma$ . A recommendation from this experience is to plan for test series consisting of more test samples, as some probably will fail during testing.
- A smaller scope, where applications are determined prior to the literature study, would be beneficial as the focus could be directed on creating a strong adhesive bond and less on where it could be implemented. With a specific application in mind, exact copies of the layer matrix could be used for the mechanical tests and yield more accurate results.

# 6

## Conclusion

When both adherends are of the same PMC material, the single-lap tensile shear strength exceeds that of the guideline for structural adhesives. Furthermore, the standard deviation is low for those test series, indicating a high success rate regarding the reliability of the bond strength. Replacing mechanical joints with adhesive bonds for PMC structures, is therefore determined to be a suitable option.

For dissimilar materials, the standard deviation was significantly higher than that of PMC adhered to PMC. This may be due to the surface treatment not being optimal when aluminium adherends are used, as well as not applying an adhesive primer to the test samples. These variations in the results for these test series highlights possible problems for implementing an adhesive bond between dissimilar adherends. However, exceptionally high tensile shear strengths were recorded for many of the dissimilar test samples. The possibility of implementing adhesive bonds for dissimilar materials is therefore promising, further research should focus on finding a better surface treatment.

The scope of the project was broad and better results could have been obtained if the material combinations for the tests had been aimed at a specific application. On the other hand, the delimitation to only look for materials available at the DSC, was reasonable as the project still had some issues with lead times, which caused a tight time frame in the end of the project. But to discover a innovative replacement for mechanical joints, other kind of materials than of those that already are present at the DSC needs to be properly investigated.

Further research is required in order to for certain determine if mechanical joints can be replaced by adhesive bonds for dissimilar materials. The environmental aspects for the tests have to be more extensive than purely looking at the influence of temperature and temperature cycling. The results from this master's thesis show promising potential for adhesively bonding dissimilar materials and can be seen as ground to build further research on.





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# A

## Production and preparation of sample pieces

Report title: Framtagning provbitar kompositlimning

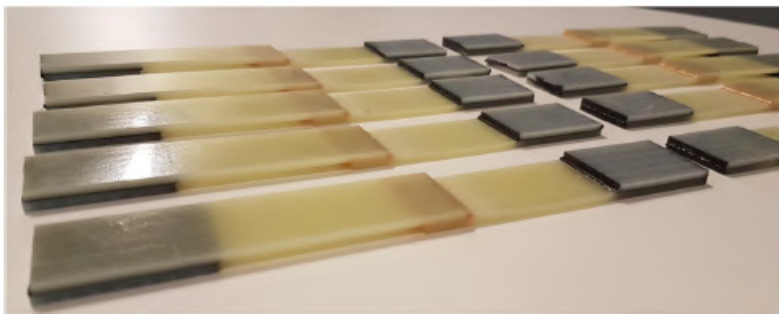
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### Framtagning provbitar kompositlimning



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## SAMMANFATTNING

Detta dokument beskriver framtagning av provbitar för kompositlimning, enligt inköpsorder 4719071.

Följande material var beställt:

1. 10st provtabbar glasfiber –  
████████████████████  
██████████  
Limmas ihop med FM300-2M, 146gsm.
2. 15st provtabbar glasfiber –  
████████████████████  
██████████  
Limmas ihop med FM300-2M, 146gsm.
3. 15st provtabbar aramid – aluminium.  
██  
████████████████████  
Limmas ihop med FM300-2M, 146gsm.

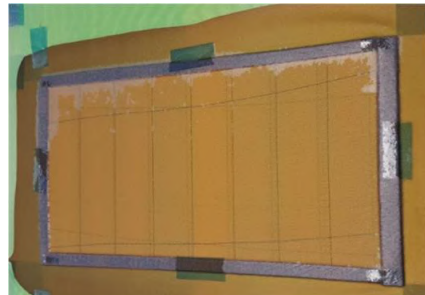
## 1 UTFÖRANDE

Stegen som utfördes var:

- Byggnation av plattorna var för sig
- Utsågning i rätt dimensioner och borring av hål för styrcinnar
- Blästring av område som ska limmas
- Rengöring och torkning inför limning (120°C i minst 16tim)
- Limning med FM300-2M.
- Härdning i 121 °C
- Vattenskarvning till korrekta mått.

### 1.1 BYGGNATION PLATTOR

En aramidplatta ██████████ togs fram, byggdes på plåt. 7 lager i samma riktningar.



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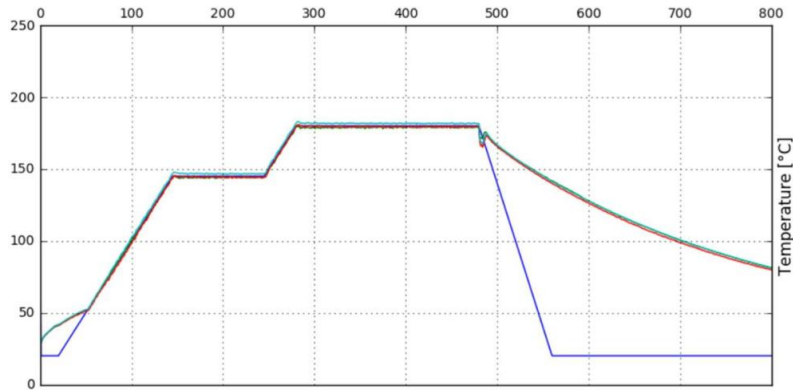
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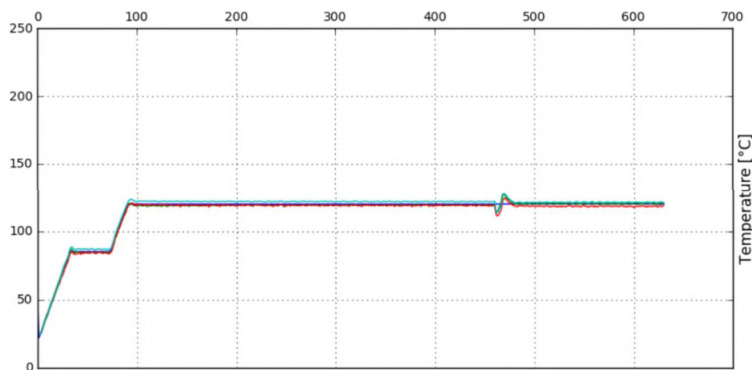


Härdades i 180°C, i härdcykel *cc\_135R\_160628\_Falcon-20200519\_08\_38*.



Två glasplattor byggs [redacted] där den första är för glasaterialet för provtabbar och den andra för materialet som limmas fast, se nummer 4 i bild med mått på första sidan. Båda plattorna byggdes med 4 lager, fiberriktning 0/90 men de två sista lagren speglade mot de två första.

Härdades i *cc\_124A\_Patientb\_150114-20200513\_17\_07*, se härdcykel nedan.



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## 1.2 UTSÅGNING OCH BORRNING

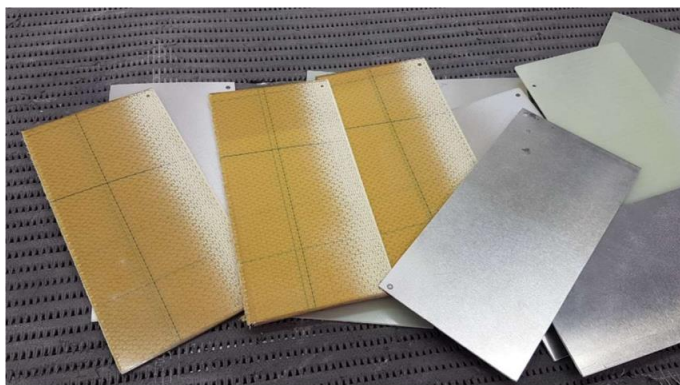
Plattor i måtten ca 200x100mm sågades ut av samtliga material.

Sedan passades plattorna mot varandra och borrning för styrhål utfördes, så att limfogsmåtten ska stämma.



## 1.3 BLÄSTRING

Blästring av områden som ska limmas utfördes.



## 1.4 RENGÖRING OCH TORKNING

Bitarna rengjordes under rinnande vatten och torkades i 120°C i ca 70 timmar.





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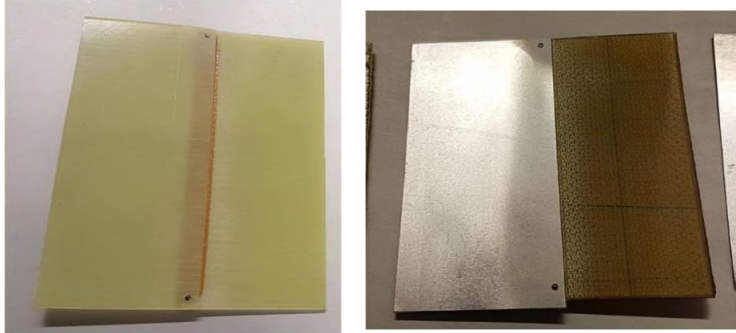
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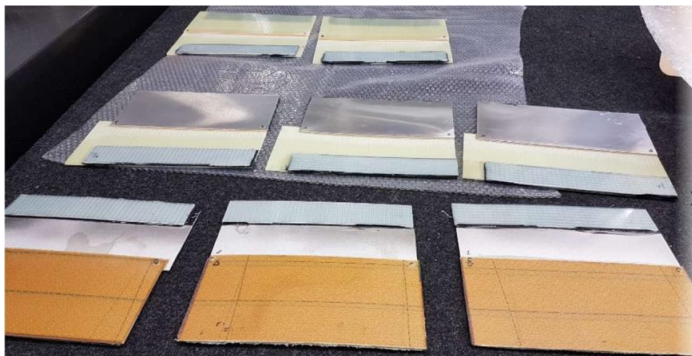
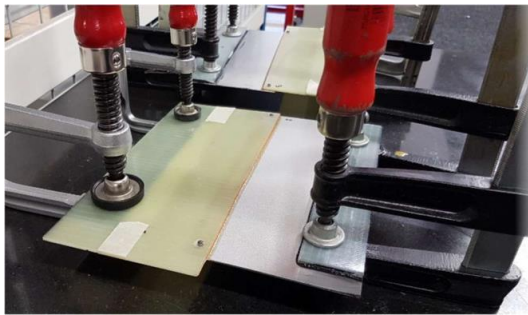
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## 1.5 LIMNING

Limning med två lager FM300-2M.



Limning av tabbarna gjordes med limmet DP490.



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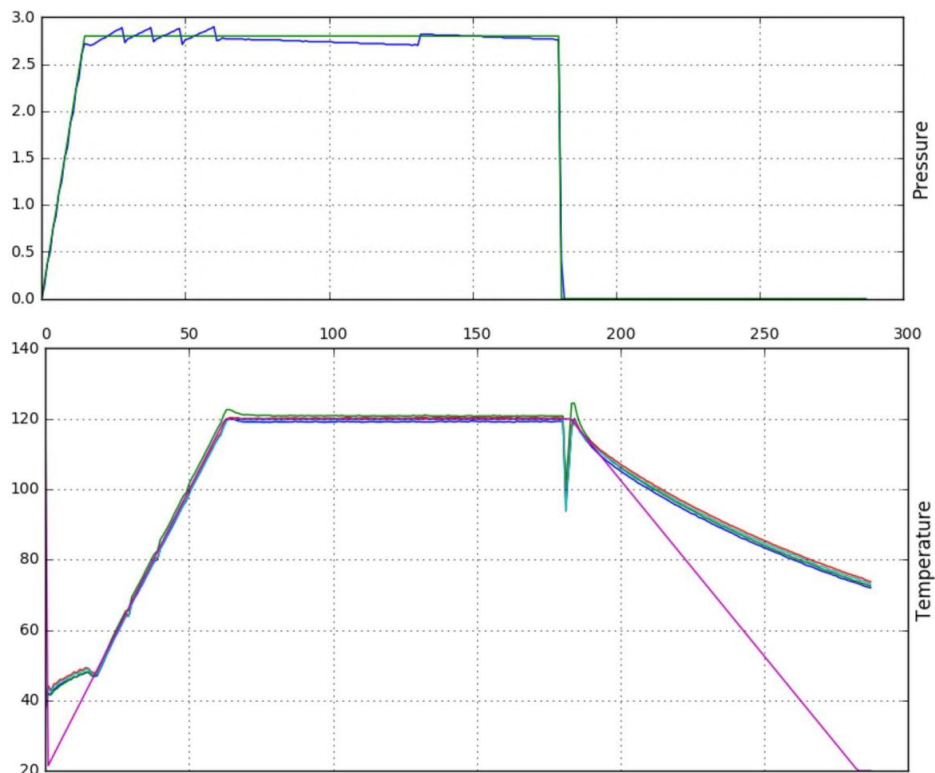
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## 1.6 HÄRDNING

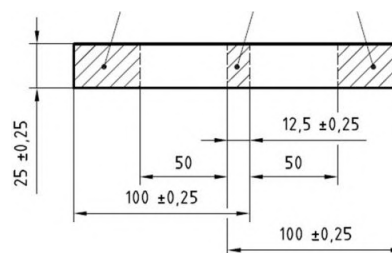
Härdades i 121°C med en ökning på 1.6°C/min under ett tryck på 0.28 MPa och ska hållas på 121°C i 90 min.

Se härdkurvans logg nedan.



## 1.7 VATTENSKÄRNING

Vattenscars till korrekta mått, dvs 187,5 x 25mm.



Report title: Framtagning provbitar kompositlimning

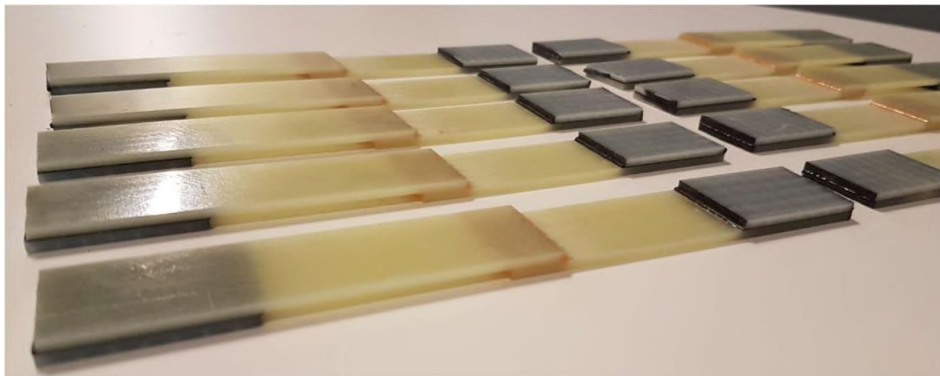
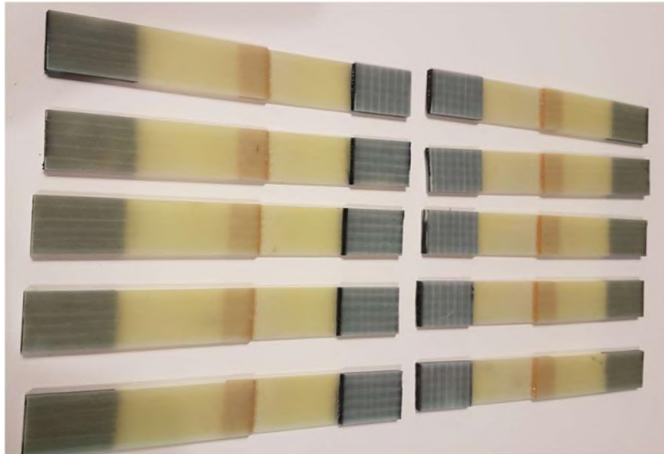
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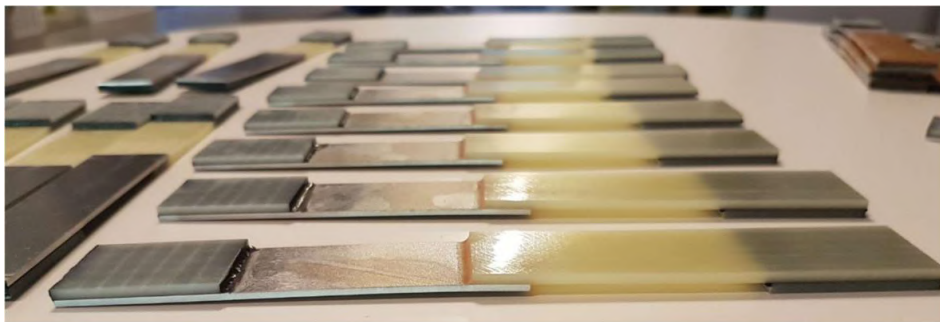
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## 1. Glasfiber – glasfiber



## 2. Glasfiber – aluminium



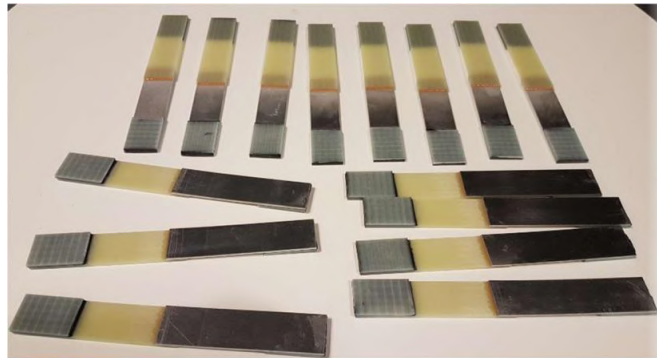
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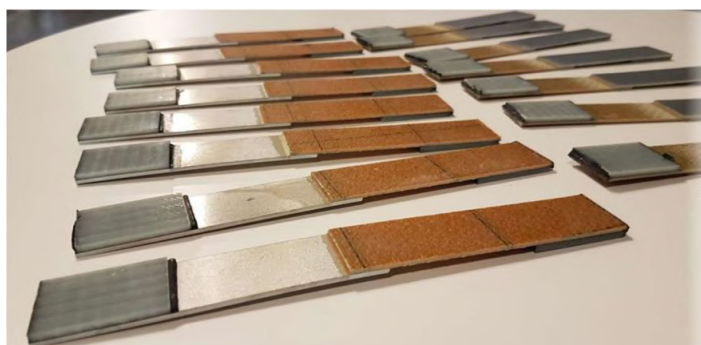
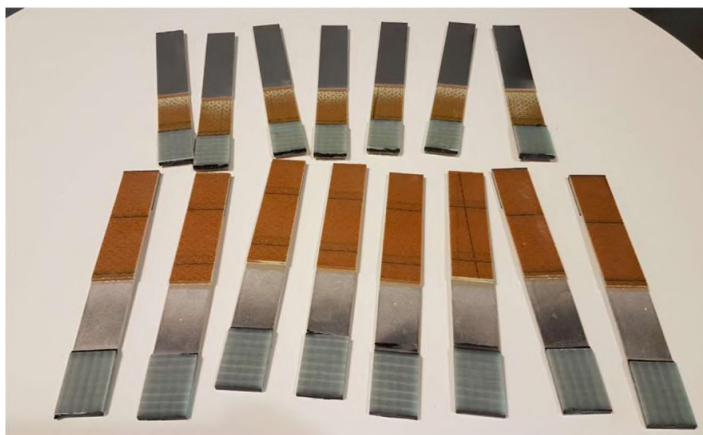
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### 3. Aramid – aluminium



# B

## Collected data from tensile shear testing

RT GFRP to GFRP			
Sample number	Strength (N)	Strength (MPa)	Displacement (mm)
1	4490	14.368	2.08
2	4763	15.2416	2.47
3	4804	15.3728	2.2
4	4534	14.5088	2.16
5	4604	14.7328	2.17
<b>Average</b>	4639	14.8448	2.216
<b>Standard dev</b>	138.7912101	0.444131872	0.148761554

High temperature GFRP to GFRP			
Sample number	Strength (N)	Strength (MPa)	Displacement (mm)
1	5070	16.224	-
2	4474	14.3168	2.39
3	4884	15.6288	2.88
4	4507	14.4224	3.3
5	4615	14.768	2.85
<b>Average</b>	4620	14.784	2.855
<b>Standard dev</b>	186.0161283	0.595251611	0.37188708

RT Al to GFRP			
Sample number	Strength (N)	Strength (MPa)	Displacement (mm)
1	3289	10.5248	1.11
2	5375	17.2	1.92
3	5270	16.864	1.65
4	4538	14.5216	1.43
5	4841	15.4912	1.85
<b>Average</b>	4662.6	14.92032	1.592
<b>Standard dev</b>	838.2388085	2.682364187	0.330181768

High temperature AI to GFRP			
Sample number	Strength (N)	Strength (MPa)	Displacement (mm)
1	4026	12.8832	2.28
2	4643	14.8576	2.73
3	1967	6.2944	0.85
4	4420	14.144	2.1
5	4589	14.6848	2.43
<b>Average</b>	3929	12.5728	2.078
<b>Standard dev</b>	1123.090602	3.593889926	0.724272048

Cyc AI to GFRP			
Sample number	Strength (N)	Strength (MPa)	Displacement (mm)
1	2673	8.5536	1.03
2	3177	10.1664	1.22
3	5429	17.3728	2.23
4	5139	16.4448	2.15
5	3058	9.7856	1.14
<b>Average</b>	3895.2	12.46464	1.554
<b>Standard dev</b>	1285.502703	4.11360865	0.585175187

RT AI to AFRP			
Sample number	Strength (N)	Strength (MPa)	Displacement (mm)
1	3772	12.0704	1.52
2	3820	12.224	0.83
3	4264	13.6448	1.29
4	4127	13.2064	0.7
5	337	1.0784	0.07
<b>Average</b>	3995.75	12.7864	1.085
<b>Standard dev</b>	238.1433392	0.762058685	0.384924235

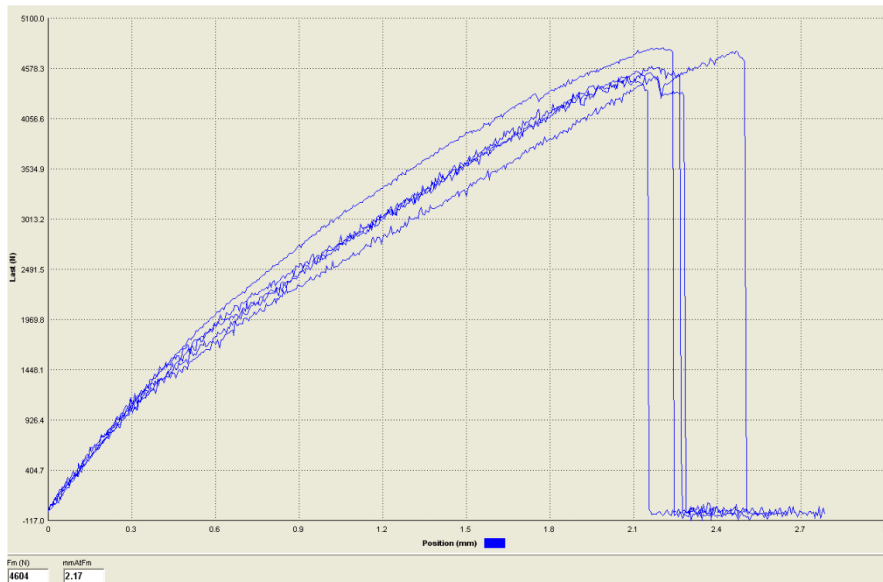
HT AI to AFRP			
Sample number	Strength (N)	Strength (MPa)	Displacement (mm)
1	278	0.8896	0.09
2	3855	12.336	1.89
3	3784	12.1088	2.25
4	424	1.3568	0.13
5	201	0.6432	0.07
<b>Average</b>	3819.5	12.2224	2.07
<b>Standard dev</b>	50.20458146	0.160654661	0.254558441

cyc AI to AFRP			
Sample number	Strength (N)	Strength (MPa)	Displacement (mm)
1	4320	13.824	2.7
2	4417	14.1344	1.43
3	410	1.312	0.7
4	3926	12.5632	2.28
5	3711	11.8752	1.62
<b>Average</b>	4093.5	13.0992	2.0075
<b>Standard dev</b>	331.8217393	1.061829566	0.588068874

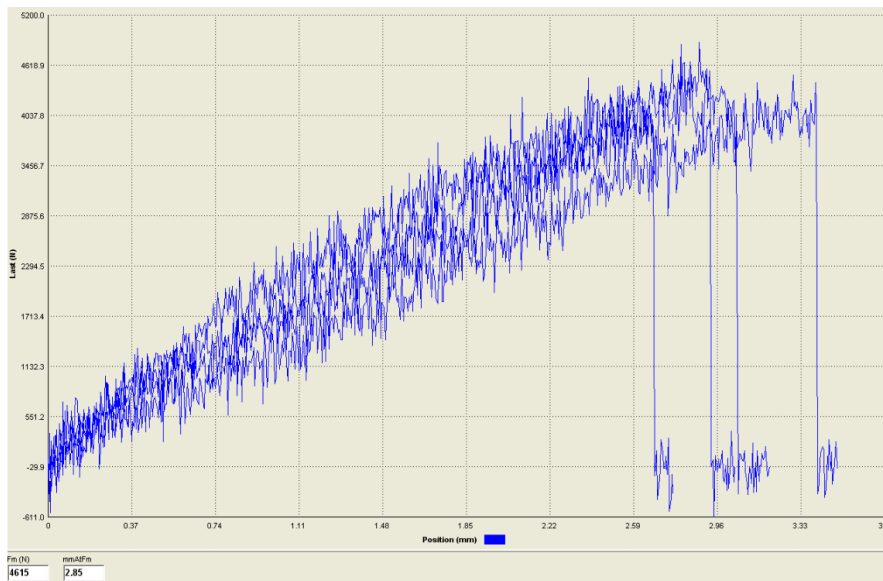
# C

## Single-lap tensile shear force against displacement

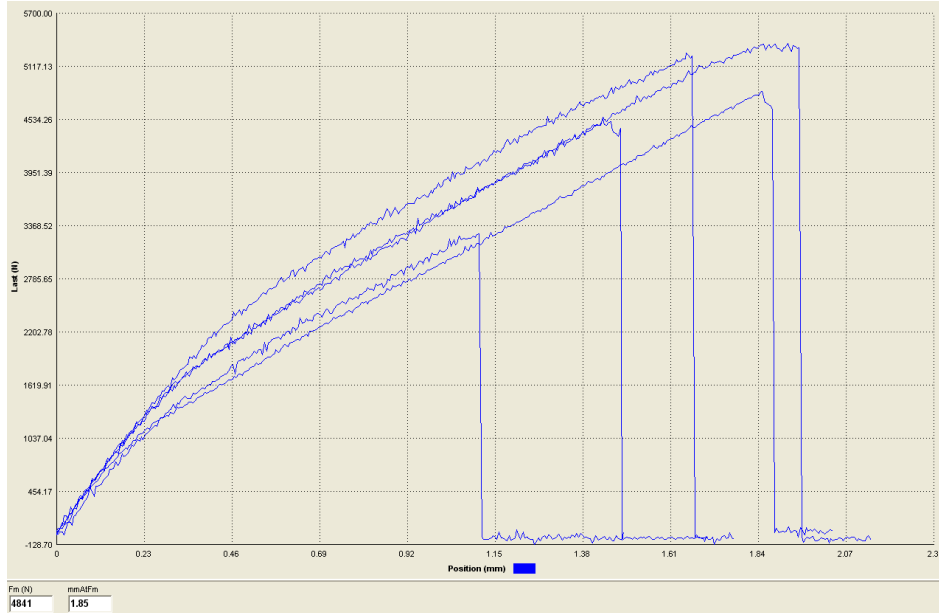
GFRP to GFRP tested at RT



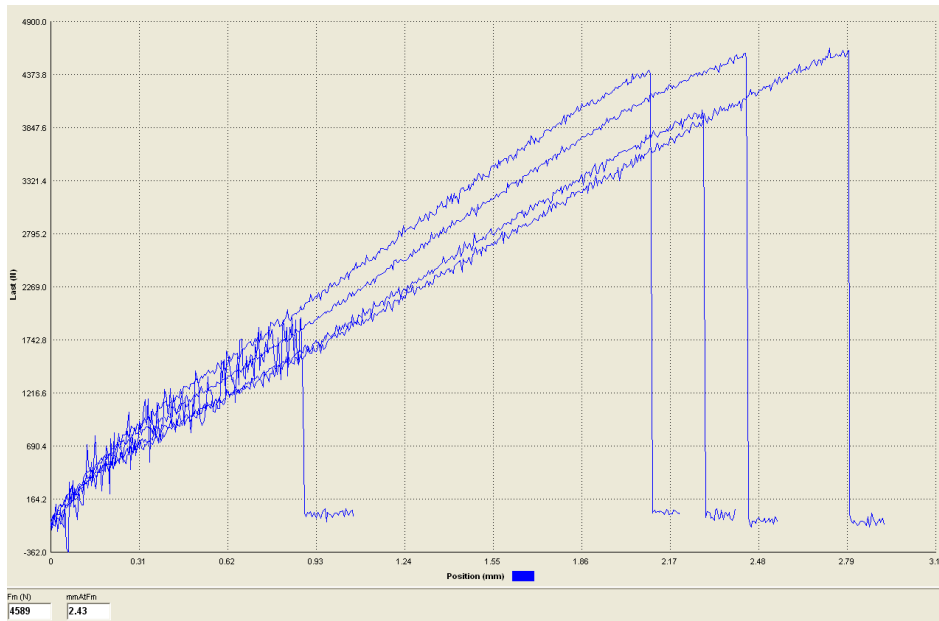
GFRP to GFRP tested at high-temperature



### GFRP to aluminium tested at RT

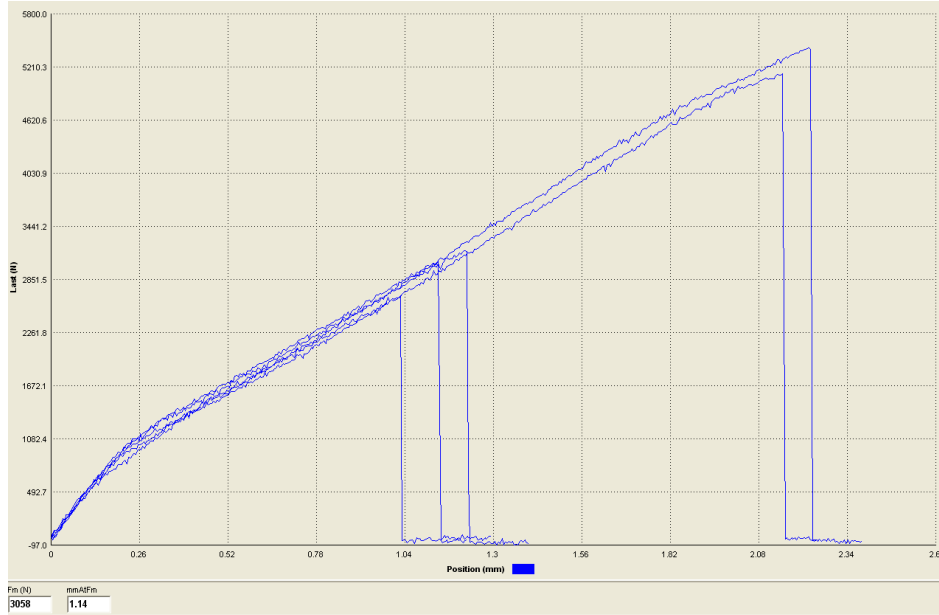


### GFRP to aluminium tested at high-temperature

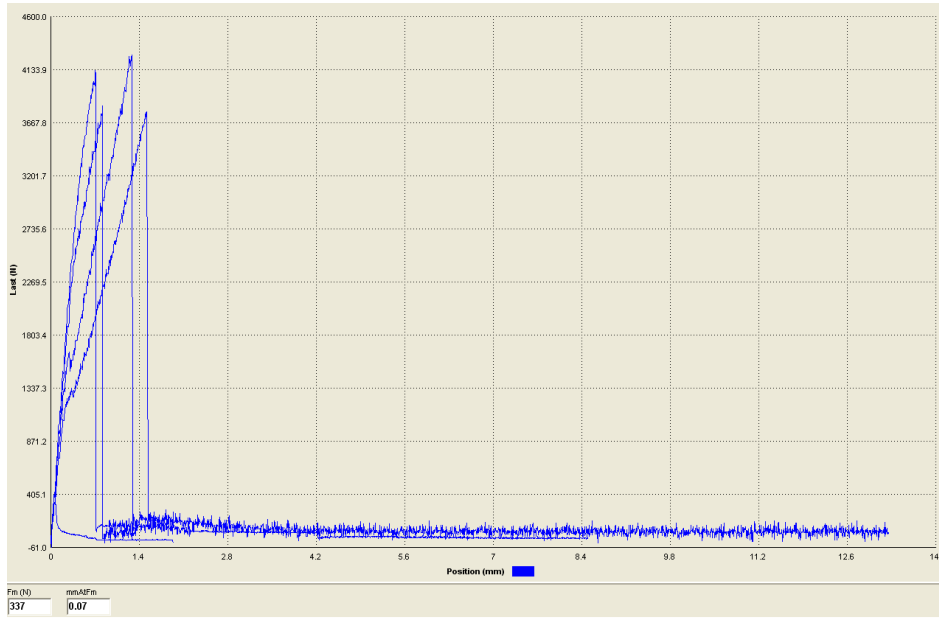




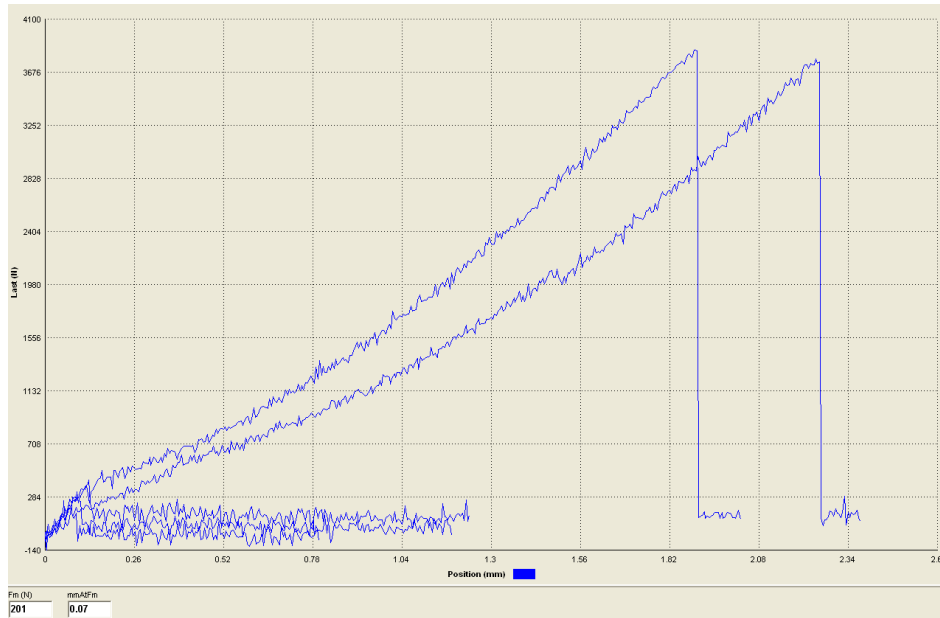
### GFRP to aluminium after cycling tested at RT



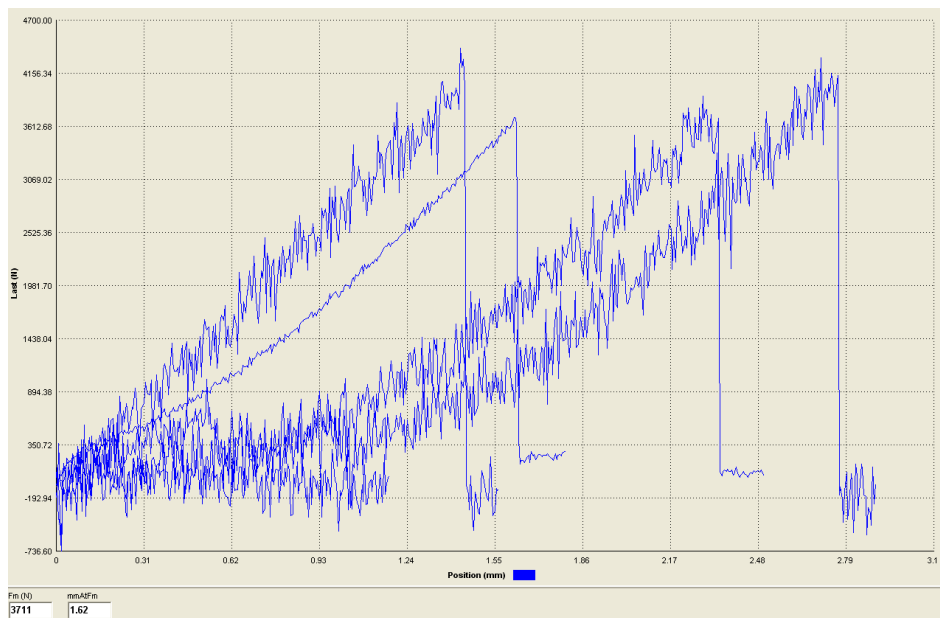
### AFRP to aluminium tested at RT



### AFRP to aluminium tested at high-temperature



### AFRP to aluminium after cycling tested at RT



# D

## Ethical Aspects

The ethical aspects considered in this master thesis have been sustainability- and workplace environment aspects.

To build products as a sandwich construction, with prepregs laminates, will result in a light-weight design. This is highly beneficial for products that have their biggest energy consumption during use, like fuel-consumption. A lower weight results in lower energy consumption. For air applications, this is extra significant. The usage of PMCs thereby results in a higher energy efficiency, which is great in the sustainability aspect.

The lower energy consumption, when using sandwich structures, has to be weighed against other perspectives when using PMCs with thermoset matrix. One of these perspectives is the ability of recycling. To recycle and reuse PMC can be difficult as they are a combination of several materials. As for prepregs, they are a small amount when it comes to the volume of PMC, which in turn are a small part of the total plastic mass (Henshaw, 2001, fig.1 fig.2). So the importance of recycling prepregs may not be because of their volume, but because of their high value (Henshaw, 2001). One option when it comes to handling waste is to prevent usage, to use less in the first place. Other options according to William Rathje (Henshaw, 2001) are burying (landfill), burning or reusing. Composites are usually used because they save weight compared to other material. For example; employing a composite in an automobile will improve fuel economy, and reduce the amount of hydrocarbon used. Seen over a life cycle a PMC can lower the overall amount of hydrocarbons consumed by that automobile, and be more advantageous than a heavier, non-fossil-based material.

The other aspect that a higher energy efficiency has to be weighed against is the workplace environment when handling thermosets. For prepregs, the matrix usually consists of thermosets, more specifically epoxy. Both PMCs chosen for this master thesis have epoxy as a matrix, and the adhesive also has epoxy as the base. Many of the substances when working with thermosets are harmful. The substances can cause allergies, asthma, skin irritation and damage mucous membrane and eyes. Thermosets are unharmed when they are fully cured, but working with them can be unsafe and preventive measures need to be taken. The preventive measures consist of; clear instructions and actions, training, protective clothing and a well-ventilated working area to minimize the risk of inhaling the harmful substances (Arbetsmiljöupplysningen, 2020).

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