



Investigation into the effect of Peel Ply surface preparation on adhesive bond performance

MA Hills

 **Orcid.org 0000-0002-9979-735X**

Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Mechanical Engineering* at the North-West University

Supervisor: Prof AS Jonker

Graduation: May 2020

Student number: 25032828

ACKNOWLEDGEMENT

Firstly, I want to thank our Saviour Jesus Christ for dying on the cross for us. Because of the cross of Calvary, he made a way for us as sinners to escape the wrath of God in the lake of fire and go to heaven to be forever with our Creator.

With that act of grace, he also sent down the Comforter, the Holy Ghost, to live in our hearts from the moment you accept Christ. The Holy Ghost gives us great peace in our hearts when going through difficult and troubling times in life and because of the Holy Ghost he made it possible for me to always stay calm during this study. All the glory to God. He must increase and we must decrease. The following two verses from the Bible served as great encouragement for me.

2 Chronicles 15:7 ~ ⁷Be ye strong therefore, and let not your hands be weak: for your work shall be rewarded.

Proverbs 3:5-6 ~ ⁵Trust in the LORD with all thine heart; and lean not unto thine own understanding. ⁶In all thy ways acknowledge him, and he shall direct thy paths.

Lastly, I want to thank my wonderful wife. She was the second source that kept me going and never gave up on me. At first, it was a big and doubtful decision to get married after a year of doing my masters. Looking back, I wish we could have been married before I even started my masters. She was a tremendous help. She always was eager to help me with my grammar and be a soundboard for ideas. I will always be grateful for her. Thank you, my wife.

ABSTRACT

An adhesive joint's strength is directly proportional to the quality of its bonding surface. One element influencing the quality of the bonding surface is the surface preparation before adhesive application. There are various methods to prepare a surface before a bond is applied, such as mechanical, chemical, and physical methods. The most-employed surface preparation method used in the industry involves sanding the surfaces with sandpaper by hand and wiping with solvent to remove contaminants. This process has several disadvantages: cost, time, dust, and limited repeatability in sanding quality. An alternative process which has become standard practice in many spheres is merely applying the adhesive to the bonding surface directly after the removal of the outer peel ply layer - with no additional surface preparation. This process eliminates all four of the previously mentioned disadvantages of the hand sanding method. An experimental investigation was initiated to examine the influence that the peel ply method has on the bonding strength and its ability to replace the hand sanding method. Double lap-shear loaded specimens were used to compare different types of peel plies with each other and with the benchmark, which was prepared using the hand sanding method. This study also investigated additional effects of surface degradation over time and surface contamination. Experimental data showed that the peel ply method outperformed the hand sanding method; however, only with certain types of peel ply. The experimental data also showed that the bonding strength decreases considerably when the bond surface is exposed to the atmosphere for more than eight hours before bonding. A similar decrease was observed when the peel ply was beforehand contaminated with carbon and glass fibre dust. Therefore, when employing the peel ply method, it is essential to control the time interval between the removal of the peel ply and adhesive application as well as the environment where the peel ply is stored.

KEYWORDS: Peel ply / Bond shear strength / Surface preparation

TABLE OF CONTENTS

ACKNOWLEDGEMENT	I
ABSTRACT	II
CHAPTER 1: INTRODUCTION	1-1
1.1 Background	1-2
1.2 Problem Statement	1-3
1.3 Objectives	1-3
1.4 Layout of the study	1-4
CHAPTER 2: LITERATURE REVIEW	1-5
2.1 Composite materials	2-6
2.1.1 Glass fibres	2-7
2.1.1.1 Properties and Applications of glass fibre	2-9
2.1.2 Carbon fibres.....	2-9
2.1.2.1 Properties and Applications of carbon fibre.....	2-11
2.1.3 Aramid fibres	2-11
2.1.3.1 Properties and Applications of aramid fibre.....	2-13
2.2 Adhesive bonding	2-14
2.2.1 Classification of adhesives.....	2-15
2.3 Surface preparation	2-16
2.3.1 Mechanical method	2-17
2.3.1.1 Grit blasting	2-17
2.3.1.2 Hand sanding	2-19

2.3.1.3	Abrasive pad scrubbing	2-21
2.3.2	Peel ply method.....	2-21
2.3.2.1	Peel ply as raw materials.....	2-21
2.3.2.2	Effect peel ply has on adherent surfaces and bond strength.....	2-22
2.3.2.3	Peel ply method in the industry	2-23
2.4	Test methods	2-24
2.4.1	Lap shear test method	2-25
2.4.2	Evaluation during lap shear test.....	2-26
2.5	Conclusion.....	2-27
CHAPTER 3: METHODOLOGY		2-29
3.1	Introduction	3-30
3.2	Tests description.....	3-31
3.2.1	The Baseline test.....	3-31
3.2.2	Variety peel ply tests.....	3-32
3.2.3	Time tests: 2-hours	3-32
3.2.4	Time tests: 8-days	3-32
3.2.5	Peel ply batch contamination test:	3-32
3.3	Experimental design.....	3-33
3.3.1	Concept design.....	3-33
3.3.1.1	Single-lap design	3-33
3.3.1.2	Double-lap design.....	3-34
3.3.1.3	Single-lap cover plate design.....	3-34

3.3.1.4	Double-lap cover plate design	3-35
3.3.1.5	Detail design: Specimen	3-35
3.3.1.6	Detail design: Bonding jig and laminates	3-37
3.3.1.7	Detail design: Calculations.....	3-39
3.4	Construction	3-40
3.4.1	Manufacture of the laminate	3-40
3.4.1.1	Cutting of materials.....	3-40
3.4.1.2	Mould preparation.....	3-41
3.4.1.3	Mixing of epoxy.....	3-41
3.4.1.4	Wet lay-up process.....	3-43
3.4.1.5	De-moulding	3-44
3.4.2	Manufacture of the test specimen	3-44
3.4.2.1	Cutting laminate into assembly laminate sizes.....	3-44
3.4.2.2	Mixing of standard flocks	3-44
3.4.2.3	Peel ply removal	3-45
3.4.2.4	Assembly and bonding using the bonding jig	3-45
3.4.2.5	De-moulding and post-curing.....	3-45
3.4.2.6	Cut into specimen sizes.....	3-46
3.5	Experimental testing	3-46
3.5.1	Apparatus	3-46
3.5.2	Test preparation	3-47
3.5.3	Perform lap shear test	3-48
3.5.3.1	Calculations.....	3-48

3.6	Conclusion.....	3-50
CHAPTER 4: RESULTS & DISCUSSION		3-51
4.1	Introduction	4-52
4.2	The Baseline test	4-53
4.3	Peel ply variety tests	4-54
4.4	Time tests with optimum peel ply.....	4-55
4.5	Peel ply batch contamination test	4-57
4.6	Conclusion.....	4-58
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS.....		4-60
5.1	Conclusion.....	5-61
5.2	Recommendations.....	5-63
BIBLIOGRAPHY		5-64
APPENDIX A		5-69

LIST OF TABLES

Table 2-1: Comparison between continuous and discontinuous fibres (Plexus, 2014) 2-6

Table 2-2: Designations of Glass fibres (Chawla, 2012) 2-7

Table 2-3: Common compositions of Glass Fibres (Chawla, 2012) 2-8

Table 2-4: Mechanical properties of E-Glass (Chawla, 2012) 2-9

Table 2-5: Classification of carbon fibres and their characteristics (Inagaki, 2000) 2-9

Table 2-6: Different groups of Carbon fibres (Park & Seo, 2011)..... 2-11

Table 2-7: Characterising of Aramid fibres (Chawla, 2012)..... 2-12

Table 2-8: Mechanical properties of different types of Kevlar (Chawla, 2012)..... 2-13

Table 2-9: Classification of adhesives (Anon, 2019) 2-15

Table 2-10: Drawbacks of the Grit blasting process..... 2-18

Table 2-11: Advantages of Grit blasting process 2-19

Table 2-12: Drawbacks of the Hand sanding process..... 2-20

Table 2-13: Advantages of the hand sanding process 2-20

Table 2-14: Drawbacks of the peel ply method 2-23

Table 2-15: Advantages of the peel ply method (Bernard, et al., 2005) 2-24

Table 2-16: Summary of the specific materials, adhesive and method used in this study 2-28

Table 3-1: Details of different tests 3-30

Table 3-2: Single-lap design’s advantages and drawbacks 3-33

Table 3-3: Double-lap design’s advantages and drawbacks 3-34

Table 3-4: Single-lap cover plate design’s advantages and drawbacks 3-34

Table 3-5: Double-lap cover plate design’s advantages and drawbacks..... 3-35

Table 3-6: Specifications of test specimens.....	3-36
Table 3-7: Dimensions and specifications of assembled laminates inside the bonding jig	3-39
Table 3-8: Summary of material calculations	3-39
Table 3-9: Specifications of Resin L 285	3-42
Table 3-10: Specifications of Hardener 287.....	3-42
Table 4-1: Summary of all tests	4-52
Table 4-2: Baseline test data.....	4-53
Table 4-3: Variety of peel ply test data	4-54
Table 4-4: 2-hour margin time test data of optimum peel ply	4-55
Table 4-5: 8-day margin time test data of optimum peel ply.....	4-56
Table 4-6: Peel ply batch contamination test data	4-58

LIST OF FIGURES

Figure 2-1: Continuous and discontinuous fibre orientation (Campbell, 2010) 2-7

Figure 2-2: Available forms of glass fibres: (a) chopped strand, (b) continuous yarn, (c) roving, (d) fabric (Chawla, 2012) 2-8

Figure 2-3: Available forms of carbon fibres: (a) strand, (b) cloth, (c) mat (Inagaki, 2000) 2-10

Figure 2-4: Available forms of carbon fibres: (a) Para-Aramid, (b) Meta-Aramid (Elliots, 2019)..... 2-12

Figure 2-5: Components of a typical adhesive joint with the ideal surface preparation applied (Petrie, 2007)..... 2-16

Figure 2-6: Grit blasting cabinet (Kay, 2016) 2-17

Figure 2-7: Hand sanding process: (a) orbital sander; (b) sandpaper (Anon., 2019)..... 2-19

Figure 2-8: Peel ply as raw material (Anon., 2014) 2-22

Figure 2-9: Example of removing peel ply (Anon., 2019) 2-22

Figure 2-10: Typical specimen of lap shear test..... 2-25

Figure 2-11: Adhesive failure (Hoke, 2005, p. 10)..... 2-26

Figure 2-12: Cohesive failure (Hoke, 2005, p. 11) 2-26

Figure 2-13: Adherend failure (Hoke, 2005, p. 12)..... 2-27

Figure 3-1: Surface finish after sanding 3-31

Figure 3-2: Single-lap design example 3-33

Figure 3-3: Double-lap design example 3-34

Figure 3-4: Single-lap cover plate design example 3-34

Figure 3-5: Double-lap cover plate design example 3-35

Figure 3-6: Final test specimen design with components..... 3-36

Figure 3-7: Specifications of the test specimens.....	3-37
Figure 3-8: Section view of bonding unit inside bonding jig.....	3-37
Figure 3-9: Process of assembling laminate and closing bonding jig	3-38
Figure 3-10: Mirror Glaze 87 release agent	3-41
Figure 3-11: Resin.....	3-41
Figure 3-12: Hardener	3-41
Figure 3-13: Resin & Hardener mixing sheet: Mixing of epoxy.....	3-42
Figure 3-14: Vacuum bagging (Anon., 2019)	3-43
Figure 3-15: Laminate after cutting.....	3-44
Figure 3-16: Cotton flocks	3-45
Figure 3-17: Peel ply removal.....	3-45
Figure 3-18: 100kN MTS Landmark Servo Hydraulic Test Bench (SHTB)	3-46
Figure 3-19: Test specimen setup on test bench	3-47
Figure 3-20: Specimen subsequent to lap shear test.....	3-48
Figure 3-21: Example of an adhesive failure type test specimen	3-49
Figure 4-1: Shear stress of Baseline Test Data	4-53
Figure 4-2: Shear stress of Variety of Peel Plies Data	4-54
Figure 4-3: Shear stress of ECC 2 Hour Margin Test Data	4-55
Figure 4-4: Shear stress of ECC 8 Days Margin Test Data.....	4-56
Figure 4-5: Shear stress of all ECC Time Tests on Logarithmic Graph.....	4-57
Figure 4-6: Shear stress of Peel Ply Contamination Test Data	4-58

CHAPTER 1: INTRODUCTION

This chapter will provide a brief background on the effect that surface preparation prior to bonding has on the manufacturing of sailplanes. The chapter will also set out the motive for this study by means of a problem statement, as well as the objectives required to solve this problem. The layout of the study will also be provided.

1.1 Background

More than two-thirds of the structure of modern sailplanes are manufactured from composite materials. Composite materials provide excellent mechanical performance, high stiffness, and strength at a low weight; hence, the reason for their extensive use. (Bernard, et al., 2005, p. 1562). One aspect that sets composite materials apart from conventional aircraft manufacturing methods is the fact that these materials can be bonded by making use of adhesives. Adhesive bonding is therefore used as the primary method of joining composite components structurally.

Since the commencement of the aviation industry, adhesives formed part of the manufacturing process. It evolved from an initial sticky concern to a ubiquitous innovation (Aerts, et al., 2005, p. 1). However, determining the strength of the bond and assessing the durability of the bond are still challenging tasks.

Several elements play a critical role in adhesive bonding, with surface preparation before the adhesive application being one of the most critical elements (Carnes & Mtenga, 2015, p. 1169). An increase in bond strength and the endurance of the bond are a result of proper surface preparation (Budhe, et al., 2017, p. 30). There are various methods to prepare the bonding surface before the adhesive application, such as mechanical, chemical, and physical methods (Serrano, et al., 2015, p. 731).

The mechanical method is preferable because of its cost-effectiveness compared to the other two methods. The most-employed mechanical surface preparation method used in the sailplane industry, called the Hand sanding mechanical method, involves sanding the surfaces with sandpaper by hand and wiping with solvent to remove contaminants. The primary mechanism employed by this method is surface roughening, which increases the contact surface area and removes the unstable and loose polymers from the bond surfaces (Ebnesajjad, 2010). The skill level required is low, but the Hand sanding method still has some weaknesses such as cost, time, dust, and limited repeatability in sanding quality (Kanerva & Saarela, 2013, p. 61).

The industry strives to make the manufacturing process as inexpensive as possible to be able to make an immense profit. Currently the Hand sanding method is the least expensive method, but it is still costly. The Hand sanding method is an immensely time-consuming method to use, especially on large bonding surfaces. The amount of dust that is created from the Hand sanding method is extremely high. Mainly it creates carbon and glass fibre dust which is unhealthy for the workers. The repeatability that the Hand sanding method provides is quite low, because the amount of pressure and sanding that each person applies is different (Kanerva & Saarela, 2013, p. 61).

The Hand sanding method was improved by adding a peel ply layer to the first and last layer of a composite layup. These layers help to protect the surface from contamination while handling or storing composite components. The peel ply layers are removed prior to bonding, and the Hand sanding method is applied to the bonding surfaces (Serrano, et al., 2015, p. 732).

In some cases, the peel ply layers are removed prior to bonding without applying the Hand sanding method, but this method, called the Peel ply method, necessitates permanent and careful monitoring to ensure the quality of the adhesive bond. (Serrano, et al., 2015, p. 732; Hart-Smith, et al., 1996, p. 2). The Peel ply method has not received the most attention in recent research, although its use can have a significant impact on the adhesive bonding of composite components (Holtmannspotter, et al., 2013, p. 97; Buchmann, et al., 2016, p. 352; Kanerva, et al., 2015, p. 41).

1.2 Problem Statement

Currently in the industry, the Hand sanding method is the most common method used to prepare a composite bonding surface prior to adhesive application. Although this method is the best method currently, the weaknesses of this method is still a big concern which are cost, time, dust, and limited repeatability in sanding quality. Therefore, there is a need for a composite bonding surface preparation method, which is cost-effective, time-efficient, dust-free and repeatable.

1.3 Objectives

1.3.1 Primary objectives

- Investigate and develop an efficient surface preparation method;
- Identify limitations of the new surface preparation method;
- Verify repeatability of the new surface preparation method.

1.3.2 Secondary objectives

- Identify the correct test method;
- Identify the correct design of the test specimen;
- Design a method to manufacture accurate, high quality, and reliable test samples;
- Collect reliable data from experiments;

- Analyse data correctly.

1.4 Layout of the study

Chapter two contains a literature study. Chapter three discusses the experimental method from the concept design of test specimens to the manufacturing of the test samples. Chapter four is dedicated to the results and evaluation. Chapter five concludes the study and discusses the recommendations for further study.

CHAPTER 2: LITERATURE REVIEW

In this chapter a brief study is done on composite materials and adhesive bonding. The term surface preparation is discussed, as well as all possible mechanical methods to use for surface preparation. The chapter also investigates which method to use for manufacturing the test specimens. Lastly, this chapter presents the most appropriate test method to determine the strength between the adhesive and the adherend prepared with the peel ply method.

2.1 Composite materials

A composite material consists of two or more materials, each having different physical and chemical properties, that are combined either through natural occurrence or engineering. This combination forms a final structure with better properties than the original materials. (Hu, 2012, p. IX). This definition might seem misleading since most materials, upon thorough examination, consist of different subunits. However, from a modern material engineering point of view, it refers to a fibre-reinforced “matrix” (Roylance, 2000, p. 1).

The term fibre-reinforced “matrix” material means that at least one of the materials is a reinforcing element, and the other is the matrix element. In most cases, the reinforcing element is a fibre which is also harder, stronger, and stiffer than the matrix element (Campbell, 2010, p. 1).

Reinforced fibres are divided into two main categories: continuous fibres and discontinuous fibres (Campbell, 2010, p. 1). The differences between these categories are displayed in Table 2-1. Figure 2-1 displays the different possible orientations of the fibre in the matrix. Reinforced fibres are further sub-categorised into glass, carbon and aramid fibres, each consisting of continuous as well as discontinuous fibres (Plexus, 2014, p. 38). Each one of these sub-categories has its own unique properties and applications.

Table 2-1: Comparison between continuous and discontinuous fibres (Plexus, 2014)

	Continuous Fibres	Discontinuous Fibres
Aspect Ratio	The aspect ratio is long.	The aspect ratio is shorter than the continuous fibres.
Orientation	These fibres have a preferred orientation (unidirectional, woven cloth, helical winding).	The orientation of the fibres is random.
Properties	The strength and stiffness of these fibres are high.	These fibres have low strength and stiffness.
Cost	The cost of these fibres is quite high compared with the discontinuous fibre.	The cost of these fibres is low.

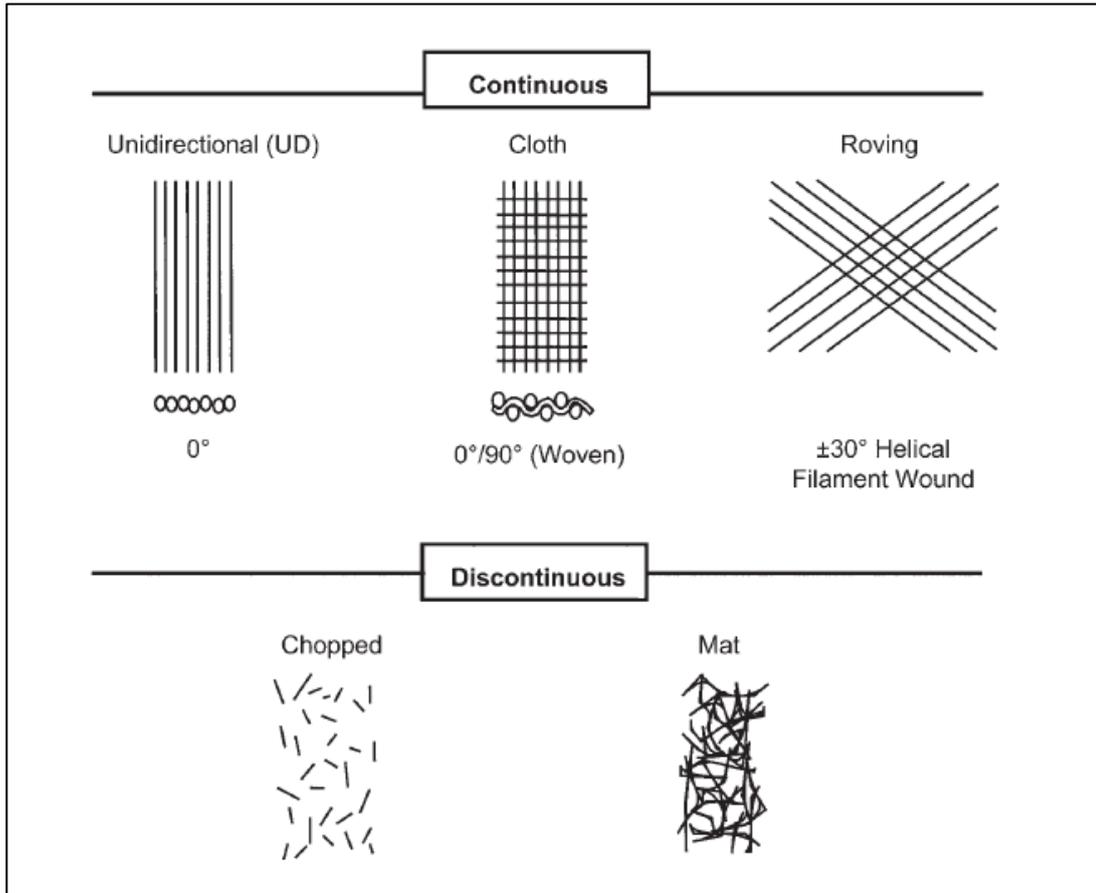


Figure 2-1: Continuous and discontinuous fibre orientation (Campbell, 2010)

2.1.1 Glass fibres

The term glass fibre is a generic name just like carbon fibre, steel, and aluminium. There exist many different glass fibres, each with its chemical composition. Silica-based glass fibres (SiO₂) are the most common and contain other oxides as well beside silicone oxide (Chawla, 2012, p. 11). Table 2-2 compares the different silica-based glass fibre classes, and Table 2-3 displays some of the conventional compositions of these glass fibres.

Table 2-2: Designations of Glass fibres (Chawla, 2012)

Glass Fibre Classes	Designation	Properties
E Glass	E: Electrical	Excellent electrical insulation along with good strength and acceptable Young's modulus.
C Glass	C: Corrosion	Good resistance against chemical corrosion.
S Glass	S: Silica	Can endure high temperatures.

Table 2-3: Common compositions of Glass Fibres (Chawla, 2012)

Compositions	E Glass (%)	C Glass (%)	S Glass (%)
SiO ₂	55.2	65.0	65.0
Al ₂ O ₃	8.0	4.0	25.0
CaO	18.7	14.0	-
MgO	4.6	3.0	10.0
Na ₂ O	0.3	8.5	0.3
K ₂ O	0.2	-	-
B ₂ O ₃	7.3	5.0	-

E-Glass is the most common glass fibre, but only a small portion of the market uses it for its designed purpose, which is to be a stand-off insulator for electrical wiring. Research later discovered that E-Glass has high fibre-forming capabilities, which resulted in a significant portion of the market using E-glass exclusively as the reinforcement fibre in the manufacturing process of fibreglass (AZoM, 2001, p. 1; Chawla, 2012, p. 12). Figure 2-2 displays various forms of glass fibres.

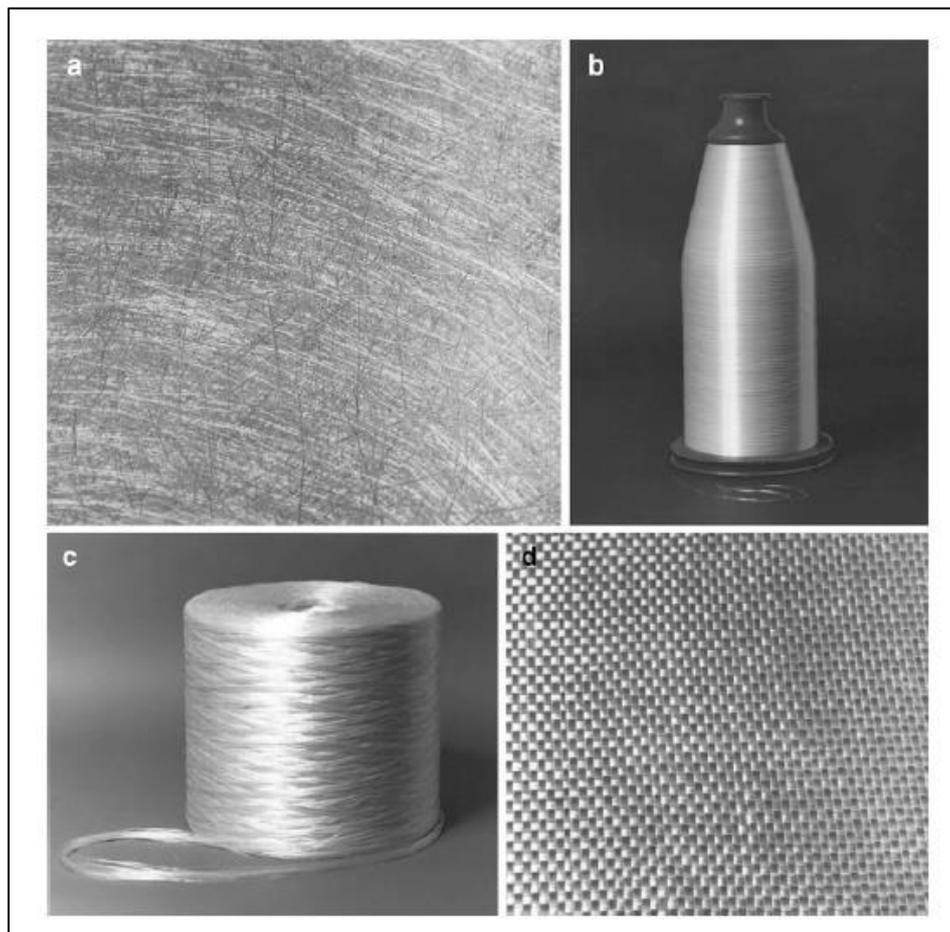


Figure 2-2: Available forms of glass fibres: (a) chopped strand, (b) continuous yarn, (c) roving, (d) fabric (Chawla, 2012)

2.1.1.1 Properties and Applications of glass fibre

Table 2-4 provides a quick summary of the mechanical properties of E-glass which includes the density, tensile strength, Young's modulus and the coefficient of thermal expansion.

Table 2-4: Mechanical properties of E-Glass (Chawla, 2012)

Density (g/cm ³)	Tensile strength (MPa)	Young's modulus (GPa)	Coefficient of thermal expansion (K ⁻¹)
2.55	1750	70	4.7 x 10 ⁻⁶

Even though the strength-to-weight ratio of E-glass is exceptionally high, the modulus-to-weight ratio is only moderately high (Chawla, 2012, p. 15). Subcritical crack growth occurs in glass fibres when a constant load is applied to it for an extended period, even though the load is safe if applied instantaneously. This observation is called static fatigue. Another disadvantage of E-glass is that its strength decreases when exposed to moisture, a feature that has to be kept in mind when using it to build aircraft (Chawla, 2012, p. 16).

The construction industry primarily uses E-glass because it is the most cost-effective reinforcement fibre. The hulls of boats use E-glass as structural fibre, and it is used to build the integral parts of structures, such as window frames, tanks, bathroom units, pipes and ducts. Other big users of E-glass are the aerospace industry and rail and road transportation industry (Chawla, 2012, p. 16).

2.1.2 Carbon fibres

Carbon fibres consist of fibres with a diameter of 5 to 10 micrometres and are composed of carbon atoms (Park & Seo, 2011, p. 432). Of all the fibres that are used to reinforce polymeric matrices, carbon fibres are by far the strongest (Jeon, et al., 2013, p. 144). Carbon fibres are classified by the precursors that have been used to produce them (Inagaki, 2000, p. 82). Table 2-5 displays the classification of carbon fibres.

Table 2-5: Classification of carbon fibres and their characteristics (Inagaki, 2000)

Classification	Precursors
PAN-based carbon fibres	Polyacrylonitrile (PAN)
Isotropic pitch-based carbon fibres	Isotropic pitch
Mesophase pitch-based carbon fibres	Anisotropic mesophase pitch
Vapour-grown carbon fibres	Hydrocarbon gases

The PAN-based carbon fibres are the most common of all carbon fibres (Matsuhisa & Bunsell, 2009, p. 575) because they provide a perfect balance between performance and cost-efficiency while obtaining high strength and a moderately high modulus. PAN-based carbon fibres in their original form allow a smooth transformation into intermediate products that are ready to be processed into carbon fibre reinforced polymers (CFRP) (Matsuhisa & Bunsell, 2009, p. 575). Figure 2-3 displays the different available forms of carbon fibres.

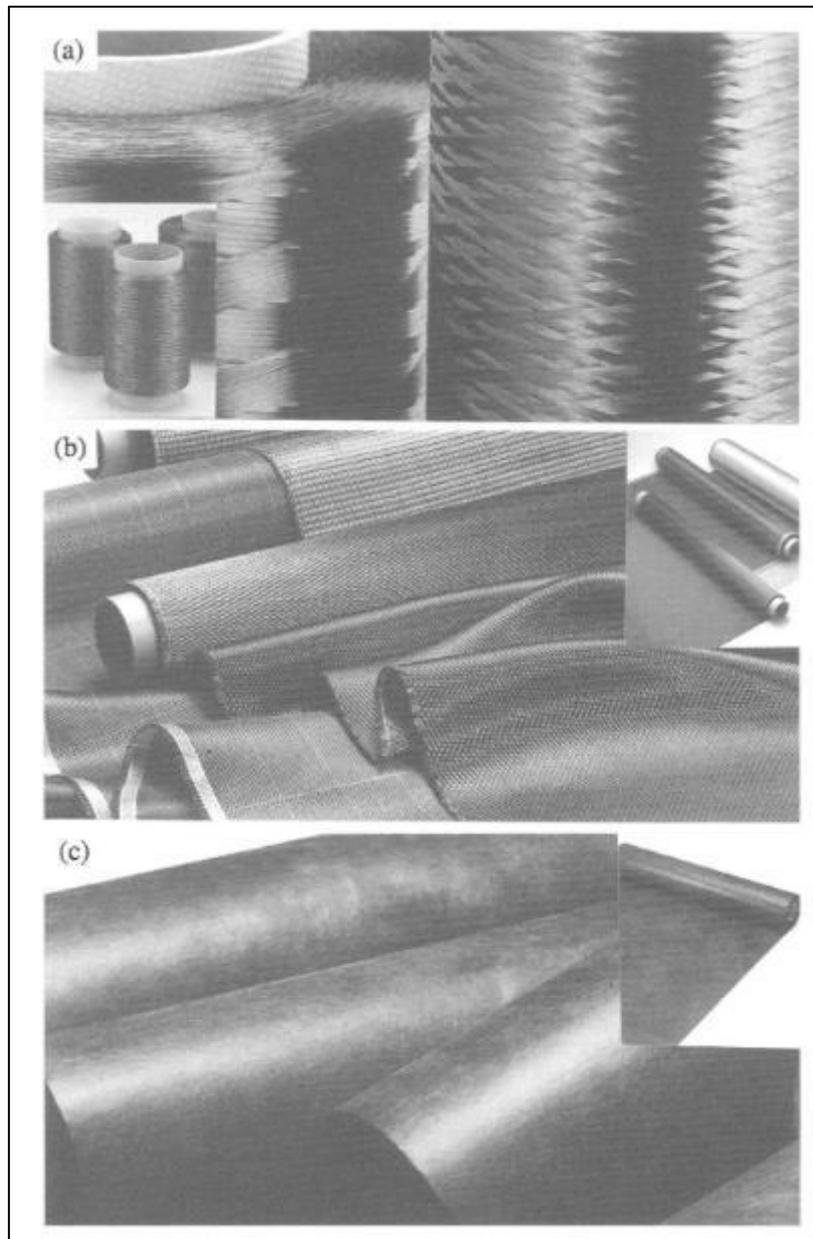


Figure 2-3: Available forms of carbon fibres: (a) strand, (b) cloth, (c) mat (Inagaki, 2000)

2.1.2.1 Properties and Applications of carbon fibre

The PAN-based carbon fibres can be categorised further into groups according to their stiffness (Young's Modulus). Table 2-6 provides a summary of the mechanical properties of the different groups of PAN-based carbon fibres.

Table 2-6: Different groups of Carbon fibres (Park & Seo, 2011)

Group of Carbon fibre	Young's Modulus (GPa)
Ultra-high modulus carbon fibres	>450
High modulus carbon fibres	350-450
Intermediate carbon fibres	300-350
Standard modulus carbon fibres	230-300
Low modulus carbon fibres	<200

Similar to glass fibre, carbon fibre also provides a high strength-to-weight ratio, but additionally, the modulus-to-weight ratio is much higher than that of glass fibre. When comparing carbon fibre to steel, it has a tremendously low density, which makes it the best material to use where low weight is required. Carbon fibres have a very high tensile strength, but lower compressive strength. It is also sensitive to shock loading (Park & Seo, 2011, p. 433). The major disadvantage of carbon fibre is the high cost of raw material compared to glass fibre.

A wide range of industries uses carbon fibre all around the world, such as the automotive industry, especially high-end racing, where low weight and high strength, is critical. In the structural engineering industry, it is mainly used to strengthen concrete, masonry, steel, cast iron and timber structures. Although carbon fibre has a high cost, it is much less expensive to reinforce structures with carbon fibre than to replace the whole structure. In the last few years, carbon fibres have become very popular in the aerospace industry because of the high strength, low weight and low thermal expansion properties. Carbon fibre has also become popular in common sports such as tennis, fishing, golf and cycling (Park & Seo, 2011, p. 434; Matsuhisa & Bunsell, 2009, p. 576).

2.1.3 Aramid fibres

Aramid fibre is a generic term for a class of synthetic, organic fibres called aromatic polyamide fibres (Chawla, 2012, p. 40). Aramid fibres consist of long-chain synthetic polyamides which make up the fibre-forming substance during the manufacturing of fibre, and two aromatic rings are directly attached to 85% of the amide linkages (Jassal & Ghosh, 2002, p. 290). Kevlar, Nomex, Twaron and Technora are well-known commercial names for aramid fibres. Aramid fibres are divided into different classes based on their Young's modulus and the type of aromatic rings of which they consist. For instance, Kevlar consists of para-orientated rings and

Nomex of meta-orientated rings (Chawla, 2012, p. 41). Table 2-7 displays the classification of aramid fibres.

Table 2-7: Characterising of Aramid fibres (Chawla, 2012)

Aramid Fibre	Characteristic	Young's Modulus (GPa)
Nomex	Regular aromatic rings	17
Kevlar 29	Regular aromatic rings	70
Kevlar 49	High modulus aromatic rings	135
Kevlar 100	Coloured aromatic rings	60
Kevlar 119	High durability aromatic rings	55
Kevlar 129	High strength aromatic rings	99
Kevlar 149	Ultra-high modulus aromatic rings	143
Twaron	Regular aromatic rings	79
Twaron HM	High modulus aromatic rings	123
Technora	Regular aromatic rings	70

The most used and studied aramid fibre is Kevlar because of its low weight and high stiffness and strength in tension (Chawla, 2012, p. 46). Kevlar and carbon fibres are usually combined in structures to be able to withstand high tensile loads and big shock (Jassal & Ghosh, 2002, p. 302). Figure 2-4 displays the different forms of aramid fibres available.

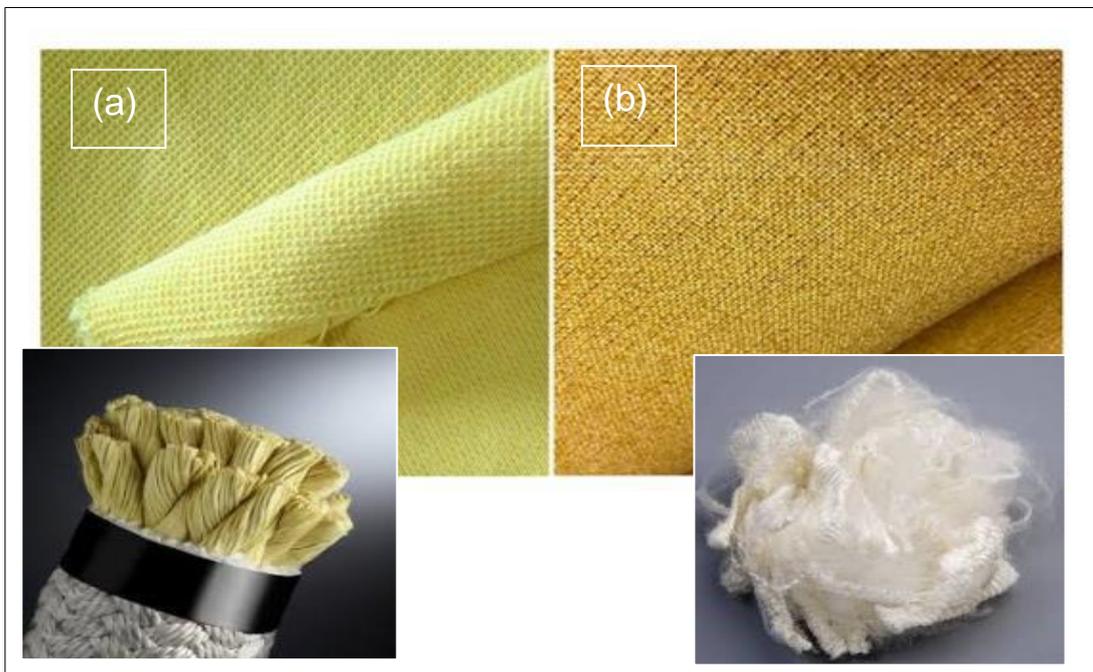


Figure 2-4: Available forms of carbon fibres: (a) Para-Aramid, (b) Meta-Aramid (Elliots, 2019)

2.1.3.1 Properties and Applications of aramid fibre

Table 2-8 provides a quick summary of the mechanical properties of different types of Kevlar which includes the density, diameter of aromatic rings, tensile strength, tensile strain fracture, Young's modulus, moisture regain and the coefficient of expansion.

Table 2-8: Mechanical properties of different types of Kevlar (Chawla, 2012)

Properties	Kevlar 29	Kevlar 49	Kevlar 119	Kevlar 129	Kevlar 149
Density (g/cm ³)	1.44	1.45	1.44	1.45	1.47
Diameter (µm)	12	12	12	12	12
Tensile strength (GPa)	2.8	2.8	3.0	3.4	2.4
Tensile strain to fracture (%)	3.5-4.0	2.8	4.4	3.3	1.5-1.9
Young's modulus (GPa)	70	135	60	99	143
Moisture regain (%) at 25°C	6	4.3	-	-	1.5
Coefficient of expansion (10 ⁻⁶ K ⁻¹)	-4.0	-4.9	-	-	-

Table 2-8 shows that Kevlar has an excellent weight-to-stiffness ratio (low density, high tensile strength) and a great weight-to-strength ratio. Kevlar 49 and Kevlar 29 are the two most popular products in the industry. Although Kevlar 29 has half the modulus of Kevlar 49, it has almost double the strain to fracture ratio than that of Kevlar 49 (Chawla, 2012, p. 49). Just like carbon fibres, Kevlar has weak compression properties, as low as 1/8 of its tensile strength; however, the vibration-damping characteristics of Kevlar are excellent. Another disadvantage of Kevlar is that its mechanical properties massively decrease when exposed to ultraviolet (UV) light. (Chawla, 2012, p. 49).

Kevlar has three specific applications: (Chawla, 2012, p. 50):

1. *Kevlar*: Rubber industries use it to reinforce the rubber in tires and other general, mechanical rubber goods.
2. *Kevlar 29*: Industries apply it during the manufacture of ropes, cables, coated fabrics for inflatables, architectural fabrics and ballistic protection fabrics.
3. *Kevlar 49*: The aerospace industry uses it for reinforcement of epoxy, polyester and other resins. Other industries, like the marine, automotive, and sports industries, employ it as well for the same purpose.

2.2 Adhesive bonding

One of the most significant challenges in designing composite structures is the joining or bonding of individual parts. (Flinn & Phariss, 2006, p. 1). The ideal method of building composite structures is to manufacture it as a single unit without any joints or fixtures, but this is not always possible. Mechanical joining methods such as bolting, riveting and screwing allow composite parts to be joined, but they cause a significant addition of weakness, fatigue and excess weight to the composite structure (Bernard & M. Fois, 2005, p. 404).

Consequently, many studies have been done to improve adhesion in order to avoid the problems of mechanical joining methods in the composite structure joining process. Adequate adhesive bonding has now enabled designers to move away from mechanical joining methods and still meet the structural integrity requirements when creating products (3M, 2016, p. 1; Bernard & M. Fois, 2005, p. 404). Petrie (2007) defines an adhesive as a substance that can permanently bond the surfaces of at least two adherends for the lifetime of the manufactured product. The following are characteristics of adhesives (Petrie, 2007, p. 3):

- They behave as a liquid during the bonding process in order to wet and flow over the surface of the adherend.
- Adhesion forms surface attachment.
- They harden to be able to withstand continuous or variable loads throughout their lifetime.
- In an assembly, they distribute and transfer loads amongst the components.
- Adhesives fill gaps, cavities and spaces.

The advantages of adhesive bonding are:

- It addresses the problem of galvanic corrosion when a composite, primarily carbon, is bonded to aluminium (Aerts, et al., 2005, p. 1).
- It has a high strength to weight ratio (Budhe, et al., 2017, p. 30).
- It offers greater design flexibility (Budhe, et al., 2017, p. 30).
- It increases durability with low overall cost (3M, 2016, p. 1).
- It seals the entire bonding area with high joint strength (3M, 2016, p. 1).
- It bonds different materials with ease (3M, 2016, p. 2).
- It distributes and transfers loads amongst the components and the entire bonded area (Petrie, 2007, p. 3).
- It offers higher stiffness than mechanical joining methods (Bardis & Kedward, 2004, p. 1).

2.2.1 Classification of adhesives

Industries worldwide manufacture approximately 250 000 different adhesives. Researchers have divided adhesives into classes based on the way they are set, on their chemical type, and on the way they are applied in assemblies. Table 2-9 lists some of the significant popular adhesive classes (Anon, 2019, p. 5).

Table 2-9: Classification of adhesives (Anon, 2019)

Adhesive class	Description
Anaerobic	When it comes into contact with metal, it cures, and prevents air bubbles from forming. Anaerobic adhesives are based on synthetic acrylic resins. Used for metals.
Cyanoacrylate	The moisture on the adherend's surface reacts with the cyanoacrylate adhesive, which causes the adhesive to cure. Joints must be tightly fitted. Used for small plastic and rubber parts.
Toughened Acrylics	Curing happens fast. These adhesives have high strength and toughness properties. Available in one- or two-part systems. Not much preparation is required. Used for a wide range of materials.
Epoxies	Epoxy adhesive systems usually consist of two components, the resin, and the hardener or curing agent. Varieties of resins and hardeners are available for use; therefore, this adhesive allows excellent versatility. Used for most materials to produce a robust and durable bond. Mostly used for composite bonding.
Polyurethanes	Fast-curing, chemically reactive adhesive. Available in one- or two-part systems. Has the best low-temperature strength and provides strong impact-resistant bonds. These adhesives are applied via a machine because of fast curing. Used for glass fibres.
Silicones	Weak adhesive. Silicones have excellent flexibility and high-temperature resistance. Available in one- or two-part systems. During the curing process, it releases alcohol or acetic acid. Used to seal baths or showers.
Phenolic	Phenolic adhesives cure through means of applied heat and pressure. Used for metals.
Polyimides	Available in liquid or film form. Can withstand temperatures up to 350 °C. It is costly and not easy to handle. Used for applications where high temperatures are present.

The epoxy adhesive is the most popular adhesive of all the available classes, and it is the best option when bonding composites, because of the variety it offers and is, therefore, the adhesive of choice for the sailplane industry. Furthermore, epoxies, which consist of a resin and a hardener, are also used as the matrix during the manufacturing of composites, along with a reinforced fibre (3M, 2016, p. 2).

2.3 Surface preparation

The key to high strength and long-term durable adhesive bond is the surface preparation before the application of the bond, as this determines the structural integrity of a bond (Bardis & Kedward, 2004, p. 1). Figure 2-5 below illustrates the components of a typical adhesive bond with the ideal surface preparation applied.

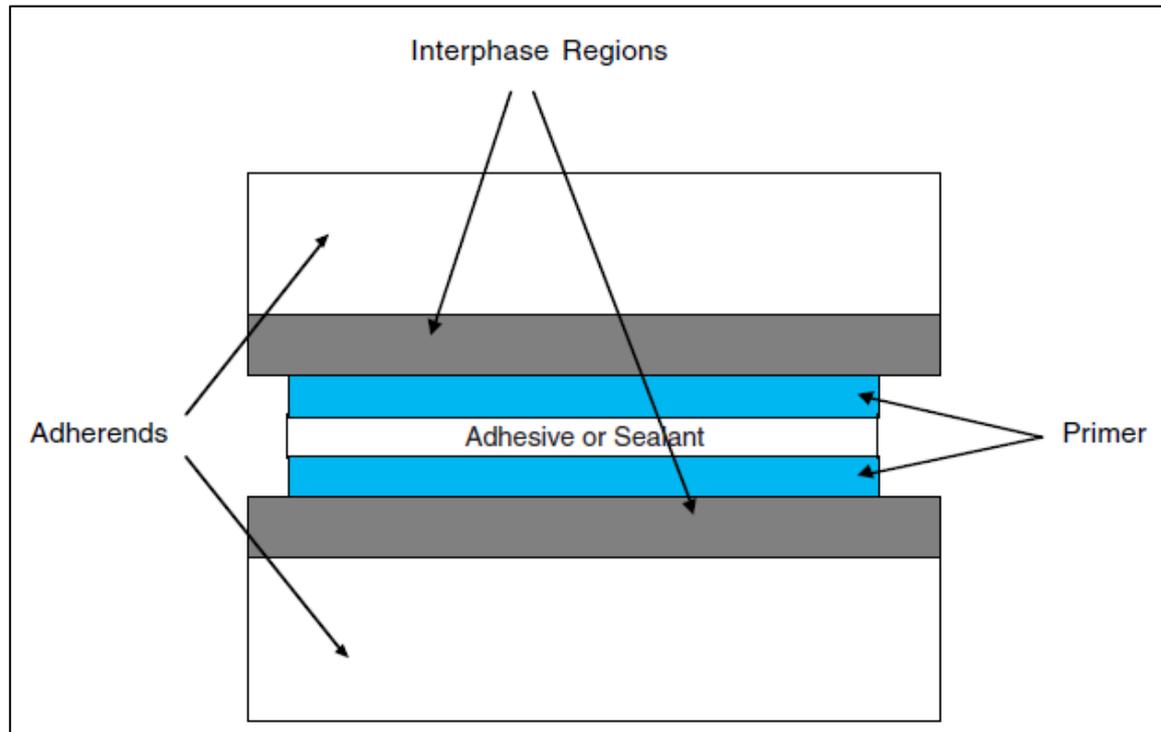


Figure 2-5: Components of a typical adhesive joint with the ideal surface preparation applied (Petrie, 2007)

Bond failures during operation have always been directly linked to weak interfaces of both metal and composite adherends. (Hart-Smith, et al., 1998, p. 29). During the adhesive bonding process, the surface of each adherend must be covered entirely with the adhesive for adequate bonding to take place.

Another factor that has a significant effect on the quality of an adhesive bond is the type of interaction between the adhesive and the adherends. A robust, attractive interaction is required for a good bond, which can only be obtained if the surface of the adherend is clean, smooth and chemically receptive before the adhesive is applied (Chemquest, 2009). All the requirements for creating a robust and lasting bond can be achieved by proper surface preparation before adhesive bonding.

Studies have shown that the different surface preparation methods result in different mechanical strengths of adhesive bonds (Woldesenbet & Aga, 2007, p. 52). The three main surface preparation methods are the mechanical, physical and chemical methods (Chemquest, 2009). For this study, only the mechanical method is discussed, since the chemical and physical methods are neither cost-effective, nor suitable for composite materials, nor are they easy to use (Bernard, et al., 2005, p. 1562). The chemical method involves surface preparation such as solvent etching or anodising, and the physical method involves surface preparation methods such as plasma, flame treatment or corona discharge (Chemquest, 2009).

2.3.1 Mechanical method

Despite its designation, the mechanical method affects the chemical attributes of the composite more than it does the mechanical attributes. The surface is roughened by the mechanical method through means of abrasion or blasting, but it is not the roughness of the surface that produces better bonds (Bardis & Kedward, 2004, p. 4). Long interlocked chains are formed during the curing phase of a composite, which then results in bonds that are created by only weak Van der Waals forces (Bardis & Kedward, 2004, p. 4). Through abrasion, the environmental contamination on the surface is removed, and the long interlocked chains are broken, which then creates a chemically active surface (Flinn & Phariss, 2006, p. 1). Thus, the abrasion exposes the long interlocked chains which allow strong ionic or covalent bonds to form with the adhesive (Bardis & Kedward, 2004, p. 4). There are several abrading processes that fall under the mechanical method: grit blasting, hand sanding, and scrubbing with an abrasive pad.

2.3.1.1 Grit blasting

Grit blasting surfaces for adhesive bonding is done by placing the adherend in a unique cabinet, displayed in Figure 2-6, and blasting a media, usually hard sand particles, onto the surface that will be bonded through a nozzle at high pressure. The media removes the contaminants from the surface to ensure a durable bond (Kay, 2016).



Figure 2-6: Grit blasting cabinet (Kay, 2016)

Grit blasting is not as commonly used as the manual abrasion process, also called hand sanding. Even though this process has been proven to be extremely useful when used for surface preparation, its inconveniences make it unpopular in industry. Table 2-10 lists all the drawbacks of the grit blasting method (Bardis & Kedward, 2004, p. 5).

Table 2-10: Drawbacks of the Grit blasting process

Drawback	Description
Cost	Blast cabinet is expensive and has a high setup cost as well (Bardis & Kedward, 2004).
Size limitations	A typical blast cabinet is a perfect size when used for test samples; however, in the aerospace industry, it is too small (Bardis & Kedward, 2004, p. 5).
Contamination	Most of the blasters make use of recirculating media. Once the media exits the nozzle onto the part, it falls back into the hopper where it gets recirculated back into the nozzle and blasted onto the part again. Eventually, the media will contain the specific contaminants that were removed from the part (Caldwell, 1999).
Mess	Fine media, dust and adherend debris exits the cabinet even though the cabinet is supposedly sealed. This creates a messy area which requires regular cleaning. Some of this dust makes it back onto the adherend before bonding (Caldwell, 1999).
Maintenance	Ensuring that the surface quality stays consistent and acceptable, cleaning the cabinet and replacing the media needs to happen frequently (Caldwell, 1999).
Training	The operators of the grit blaster must be well-trained to use it safely and consistently (Bardis & Kedward, 2004, p. 5).
Over-abrasion	Over-abrasion occurs more frequently with a grit blaster than with other abrading processes. The outer layer of the composite matrix can be removed, and the fibres exposed if the grit stream stays on one location of the composite for too long (Davis & Bond, 1999).

Although there are several drawbacks to the grit blasting process, there are some advantages which are listed in Table 2-11.

Table 2-11: Advantages of Grit blasting process

Advantages	Description
No contact	During the hand sanding process, the contaminants that are removed are transferred back to the sandpaper and potentially redeposited back on the abraded surface. However, during the grit blasting process, the dust build-up is kept to a minimum by the dust collector, as well as with the continuous airflow (Davis & Bond, 1999).
Consistency & Repeatability	In order to repeat the grit blasting process consistently, an optimal blasting setup needs to be determined. Once the setup is done, the repeatability of the process is possible. The ease and consistency of regulating the blast pressure also influence the repeatability (Hart-Smith, et al., 1996).
Safety	No dust mask is required during the process. The cabinets are sealed and have a built-in dust remover. Even though this process creates a mess, it is only in and around the cabinet, but small debris gets airborne (Bardis & Kedward, 2004, p. 5).

2.3.1.2 Hand sanding

Hand sanding, also known as the manual abrasion process, makes use of sandpaper or an orbital sander to abrade the adherend surfaces before bonding. A solvent wipe is required after abrasion, directly before bonding, to remove the debris created by the abrasion (Ebnesajjad, 2010, p. 52). Figure 2-7 displays the hand sanding process.



Figure 2-7: Hand sanding process: (a) orbital sander; (b) sandpaper (Anon., 2019)

There are a few reasons why the hand sanding process is inferior to the grit-blasting process. However, owing to its cost-efficiency and simplicity, the hand sanding process is still the most popular in the industry (Bardis & Kedward, 2004, pp. 3-8) despite its drawbacks, which are listed in Table 2-12.

Table 2-12: Drawbacks of the Hand sanding process

Drawbacks	Description
Contamination	The hand sanding process is a contact process, which means that the removed contaminants can be redeposited back onto the adherend's surface. This can happen in two ways. Firstly, dust and debris containing the surface contaminants are released when the outer layer of the epoxy matrix that has been cut through by the abrasive grit. Secondly, the contaminants are trapped in the sandpaper and redeposited back to the adherend's surface (Bardis & Kedward, 2004, pp. 3-8).
Inconsistency	If the surface of the adherend is not flat, it is difficult to achieve consistency. The applied pressure of sanding is also not consistent from operator to operator nor from day to day (Hart-Smith, et al., 1998).
Uneven surface	Differing amounts of sanding pressure are applied across the surface, creating an uneven surface with contours and hollows. This allows contaminants and moistures to be trapped on the surface (Davis & Bond, 1999).
Mess	Grit blasting and hand sanding create almost the same amount of dust and debris; however, during the grit blasting process, most of the dust and debris are caught in the cabinet. During the hand sanding process, the dust and debris are airborne and distributed across the room. This is a hazard for the technicians.

Despite all these drawbacks, the hand sanding process has several advantages to validate its popularity in the industry (Bardis & Kedward, 2004, pp. 3-9). These advantages are listed in Table 2-13.

Table 2-13: Advantages of the hand sanding process

Advantages	Description
Cost	Hand sanding is cost-effective. This makes it the preferred choice to the grit blasting process (Bardis & Kedward, 2004, pp. 3-9).
Training	The hand sanding process requires almost no training, and when training takes place, the time and cost are deficient. This is because sandpaper is a common household item, and most technicians have used it before (Bardis & Kedward, 2004, pp. 3-9).
No size limitations	There are no size limitations when using the hand sanding method. Any surface size can be prepared through the hand sanding method (Bardis & Kedward, 2004, pp. 3-10).

2.3.1.3 Abrasive pad scrubbing

The abrasive pad scrubbing process is almost the same as the hand sanding process. The difference is that the abrasive pad scrubbing process takes much longer. This results in removing contaminants much slower compared to the hand sanding process, which creates less dust and debris (Bardis & Kedward, 2004, pp. 3-10).

The downside of this process is that it creates grooves on the surface which leaves small traces. This results in weak bonding and inconsistency in the abrasive pad scrubbing method. The most common abrasive pad that is used is the 3M's nylon Scotch-Brite pad. The abrasive pad scrubbing process is the least used in industry (Bardis & Kedward, 2004, pp. 3-10).

2.3.2 Peel ply method

Another surface preparation method that is widely employed in the composite industry is the peel ply method. This method entails simply by adding a peel ply layer to the first and last layer of a composite lay-up schedule. The peel ply layers are then removed prior to bonding with no additional surface preparation. Peel plies are cost-efficient and easy to use. There are intensive studies on peel plies themselves; however, studies on applying only the peel ply method as a surface preparation method are few. At the moment the Hand sanding method is applied after the peel plies are removed (Bernard, et al., 2005, p. 1562; Kanerva, et al., 2015, p. 40).

2.3.2.1 Peel ply as raw materials

Peel plies are synthetic fabrics containing three primary fibres, which are perpendicularly woven: polyester, polyamide and glass (Kanerva & Saarela, 2013, p. 61). Peel plies were designed for the following reasons (Kanerva & Saarela, 2013, p. 61; Holtmannspotter, et al., 2013, p. 97; Buchmann, et al., 2016, p. 352).

- Peel ply absorbs the excess resin during the manufacturing process.
- It protects the composite surface from contamination during handling, storing and transporting.
- It produces a surface that is clean, rough, and that has a specific surface morphology.

Peel plies are treated with a release agent in order to facilitate removal from the laminate preceding bonding (Holtmannspotter, et al., 2013, p. 97; Kanerva, et al., 2015, p. 40). When removing the peel ply, a certain amount of the release agent is left behind on the bonding surface. This release agent is seen as a contaminant on the bonding surface (Kanerva & Saarela, 2013, p. 61; Hart-Smith, et al., 1996, p. 2), which is why the Hand sanding method is applied for further surface preparation prior to bonding (Kanerva & Saarela, 2013, p. 61).

However, the amount and type of release agent found on the various types of peel plies affect the bond shear strength in different ways. There are also certain types of peel plies that have been heat-set and scoured (Kanerva & Saarela, 2013, p. 61). In some cases, there is no release agent present on the peel plies (Gardner, et al., 2013, p. 2). Figure 2-8 displays an example of peel plies in the industry.



Figure 2-8: Peel ply as raw material (Anon., 2014)

2.3.2.2 Effect peel ply has on adherent surfaces and bond strength

There are two main effects that peel plies have on the surface of the composite. Firstly, there is an interaction between the peel ply and the composite matrix resin, which means that when the peel ply is removed, a certain amount of peel ply material or impregnation resin is left behind on the surface of the composite. This may result in a weak bond (Budhe, et al., 2017, p. 31; Kanerva & Saarela, 2013, p. 61).

Secondly, when the peel ply is removed, it leaves the composite surface with a specific roughness. The result is that a mechanical bond can form because the rough surface makes it possible for the flow of the adhesive in and around the disproportions on the bonding surface (Carnes & Mtenga, 2015, p. 1169). Figure 2-9 displays an example of peel ply being removed from a laminate.

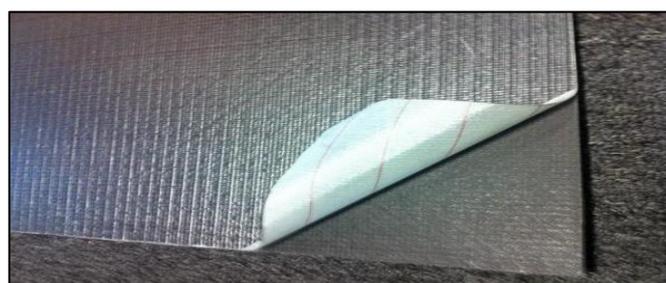


Figure 2-9: Example of removing peel ply (Anon., 2019)

According to some researchers, using only the peel ply method for surface preparation has a detrimental effect on the bond shear strength of an adhesive bond when compared to the Hand sanding method (Budhe, et al., 2017, p. 31; Kanerva & Saarela, 2013, p. 61). There are two reasons why this was observed. The first being that the release agent left behind on the bonding surface after the peel ply is removed, prevents the adhesive from bonding to the surface (Hart-Smith, et al., 1996, p. 5).

The second reason is that when the peel ply is removed from the composite, the bond surface is left with lumps or irregular borders, which results in cavities forming inside the adhesive bond reducing the bond shear strength (Kanerva & Saarela, 2013, p. 61).

2.3.2.3 Peel ply method in the industry

When the peel ply method was introduced, it was combined with the Hand sanding method. Research proved that abrasion is needed after the removal of peel ply to ensure the release agents are removed from the adherend's surface (Hart-Smith, et al., 1996, p. 5).

Table 2-14 lists and explains the drawbacks of the peel ply method on why it is not used by itself.

Table 2-14: Drawbacks of the peel ply method

Drawbacks	Descriptions
Release agent	Peel plies are treated with different types of release agents and with differing amounts of release agent. Some of the release agents stay behind on the adherend's surface, which then necessitates the use of the mechanical method before bonding (Kanerva & Saarela, 2013, p. 61; Hart-Smith, et al., 1996, p. 24).
Contamination	If the peel ply fabric is not stored correctly, it can get contaminated, which will then have a significant influence on the bond strength (Hart-Smith, et al., 1996, p. 4).
Time limit	After the removal of the peel ply, the adhesive needs to be applied to the adherend's surface immediately to avoid contamination (Hart-Smith, et al., 1996, p. 2).
Uncertainty	Only a few studies have been done on the durability and strength of an adhesive bond where the surface is prepared only with the peel ply method. This is the biggest reason why the peel ply method is not used by itself in the industry (Kanerva, et al., 2015, p. 40).

By means of proper process design, good storing and handling practises and identification of the best peel ply to use with the peel ply method, all the drawbacks in Table 2-14 can be avoided. The uncertainty of using only the peel ply method can be solved with further tests and

studies on the method. Even though there are some drawbacks, the peel ply method has multiple advantages which are listed in Table 2-15 (Bardis & Kedward, 2004, pp. 3-10).

Table 2-15: Advantages of the peel ply method (Bernard, et al., 2005)

Advantages	Descriptions
Cost	Peel ply is extremely cost-effective compared to the grit blasting method. The hand sanding method is more cost-effective than the peel ply method, but only by a small margin (Bernard, et al., 2005, p. 1562).
Time	It is much more time-efficient than both the hand sanding method and the grit blast method.
No mess	No mess is involved when using the peel ply method. No abrasion is used in the peel ply method. Only dustbins are required for the removed peel ply.
No limitation in size	Peel ply is the first and last layer of a composite. Therefore, the whole surface is covered with peel ply.
Training	If the technicians can build a composite component, then they can also use peel ply. Peel ply fabric is treated the same way as a composite fabric. It is a standard layer in a lay-up schedule. The only training required is how to remove the peel ply from the adherend's surface.
No contact	There is no contact on the adherend's surface during the peel ply method. The peel ply is removed, and the adhesive can be applied directly. No additional abrasion or solvent wipes are required.
Repeatability	The peel ply method has excellent repeatability if procedures are followed.

2.4 Test methods

Whenever a new product or method is introduced in the engineering industry, the durability and behaviour of the product or method must be determined. Therefore, engineers have developed and initiated test methods in order to predict the durability and behaviour of every new product or method. Through these test methods the validity and reliability can be determined (Bonk, et al., 1996, p. 1).

There are many different short-time test methods that can be used to assess adhesive bonds. Some of which are T-peel tests which measure the peel strength of a bond, impact strength tests which measure the impact strength and lap shear tests which measures the shear strength.

In order to determine the validity and reliability of the peel ply method, the shear stress between the adhesive and the adherend must be determined. The lap shear test will be used for this

study because it is the only test method that measures shear strength exclusively (Bonk, et al., 1996, p. 1).

2.4.1 Lap shear test method

The lap shear test, ASTM D 1002, is most commonly used for the evaluation of shear stress of adhesive bonds. The manufacturing of this test specimen is inexpensive and easy. The only apparatus required to perform the tests is a tensile testing machine with self-aligning grips. The test apparatus must also be able to maintain a loading rate of 8.3 to 9.7 MPa/min (Bonk, et al., 1996, p. 1). Figure 2-10 provides an example of a typical lap shear test specimen.

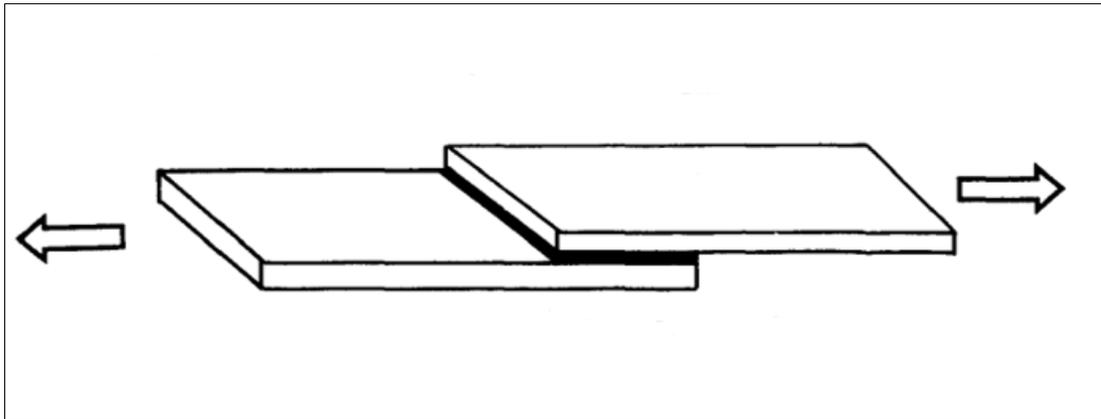


Figure 2-10: Typical specimen of lap shear test

After the test specimens are manufactured, they are tested until failure. The highest load attained by each specimen is recorded, and these values are designated the lap shear strength (Cooper & Sawyer, 1979, p. 1). One shortcoming of the standard lap shear test is that the construction of the specimen is not symmetric. Therefore, there is not only shear stress involved during tests, but also a bending moment which causes the specimen to deform or fail prematurely. The result is that concentrated stresses are experienced at the edge of the bond (Bonk, et al., 1996, p. 1), because the applied force is not parallel to the plane of the bond (Cooper & Sawyer, 1979, p. 6). If these forces exceed the adherend's yield strength, it can cause the specimen to fail prematurely.

There are other factors that influence the results of the lap shear test, including the type of adhesive used, the thickness of the adhesive and adherend, the surface preparation of the adherend, and the modulus and yield strength of the adherend (Bonk, et al., 1996, p. 2).

2.4.2 Evaluation during lap shear test

Prior to any calculations, all specimens must be examined to determine what failure mode occurred to each of them. During the lap shear test, there are three main failures that can occur to the specimen.

Adhesive failure:

Adhesive failure occurs when the bond between the adhesive and the surface of the adherend fails. A load value captured on this type of failure gives an indication of the quality of the surface preparation prior to adhesive application (Hoke, 2005, p. 10). In this study, only the data from specimens that experienced this failure was considered valid. Figure 2-11 provides an example of an adhesive failure.



Figure 2-11: Adhesive failure (Hoke, 2005, p. 10)

Cohesive failure

Cohesive failure occurs when the bond fails within the adhesive layer. This failure indicates that the adhesive was poorly cured, or moisture was present in the adhesive (Hoke, 2005, p. 11). If this failure occurred during testing, the data was classified as invalid. Figure 2-12 provides an example of cohesive failure.

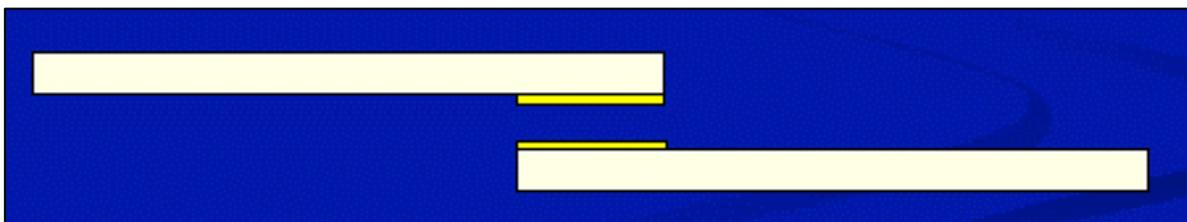


Figure 2-12: Cohesive failure (Hoke, 2005, p. 11)

Adherend failure

Adherend failure is when the adherend fails before the bond. This is caused by an interlaminar fracture in the composite structure, and it is an indication of brittle epoxies, or of dry patches inside the laminate (Hoke, 2005, p. 12). If this failure occurred during experiments, the data were classified as invalid. Figure 2-13 provides an example of an adherend failure.

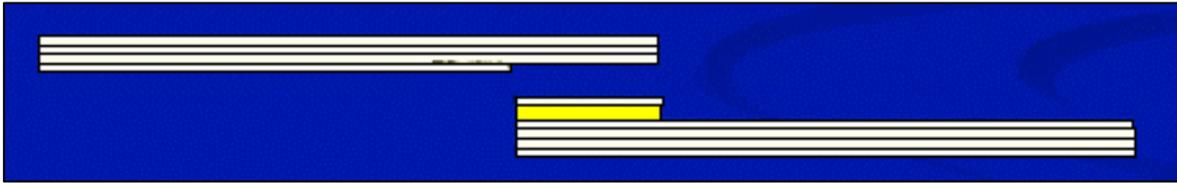


Figure 2-13: Adherend failure (Hoke, 2005, p. 12)

2.5 Conclusion

This literature survey reviewed four main subjects: the different types of composite materials, the various types of adhesive bonding used in industry, the different types of surface preparation methods, and the test methods used to test an adhesive bond.

The first section discussed the differences between glass, carbon and aramid fibres. All three of these composite materials are used in the aerospace industry with each one contributing a distinct attribute to the structure of a component. However, any one of these three composite materials would be serviceable to determine the strength of the adhesive bond. Since all three consists of fibres, they will yield the same results concerning different surface preparation methods when tested. In this study, E-glass fibres were used to build the test samples, because it is the most inexpensive.

In the second section, it was shown that epoxy resin has the best mechanical properties and is, therefore, the adhesive of choice for the sailplane industry. It will, therefore, be used as the adhesive in this study.

The third section concluded that physical and chemical methods are not cost-effective compared to the mechanical method for surface preparation. The grit blast method will not solve the problem of this study owing to some specific drawbacks, most significantly, the creating of dust. The hand sanding method is not consistent enough and requires a great deal of attention to prevent contamination. It was concluded that the peel ply method has the potential to solve the problem – if an optimum peel ply can be identified, and if the limitations of the method can be delineated. Further tests must, therefore, be done on the peel ply method.

In the fourth section, the lap shear test method was identified as the best test method to use for this study. The reason being that the lap shear test method measures shear stress only. The highest tensile load attained by a bond is directly related to the strength of the adhesive bond. The failure modes that can occur to a test specimen during testing was also discussed. It was found that the only acceptable failure mode during testing is the adhesive failure mode.

The conclusion of the literature review is that there is a need for a method to prepare a surface prior to adhesive bonding, which is cost-effective, time-efficient, dust free and repeatable. Table

2-16 provides a summary of the specific materials, adhesive and method that are used in this study.

Table 2-16: Summary of the specific materials, adhesive and method used in this study

Division	Selection
Composite material	E-glass
Adhesive	Epoxy adhesives with added cotton flocks
Surface preparation method	Peel ply method
Test Method	Lap shear test method

CHAPTER 3: METHODOLOGY

This chapter starts off with a road map of all tests that was conducted in this study. The design of the test specimens is also addressed, as well as the best method to manufacture high quality and reliable test samples. Additionally, the ideal test setup is explored.

3.1 Introduction

The previous section showed that peel ply method has the potential to replace the hand sanding mechanical surface preparation method. The suitability was experimentally investigated by comparing the bond strength of the peel ply method with that of the hand sanding method. The minimum bond strength values for the sailplane industry is well known (Schoberth, et al., 2017, p. 7) and this was confirmed in a base line test where the bond strength of a mechanically prepared bond was tested. This was followed by tests with peel ply. It was quickly discovered that there are many different peel ply materials on the market and a selection of different peel ply materials was tested in the variety peel ply tests.

From the literature study, it was suspected that the time between peel ply removal and adhesive application will influence the bond performance (Hart-Smith, et al., 1996, p. 2). The next set of tests was the time tests. These tests were performed through means of the peel ply method by removing the peel ply layers and leaving the bond surface open to the atmosphere for a duration of 2 hours with 30-minute intervals and 8 days with 2-day intervals before the bond was performed.

Lastly, the effect of dust contamination of the peel ply before use, was investigated. A summary of the different tests is displayed in Table 3-1 and a detailed explanation of each of these tests is given in Section 3.2.

Table 3-1: Details of different tests

Test Description	Surface preparation	Time between removal of peel ply and application of bond	Peel ply batch condition	Reason for test
Baseline test	Hand sanding mechanical method	None	Peel ply was not used	To obtain a baseline value to which the peel ply method can be compared.
Variety peel ply test	Peel ply method	None	Uncontaminated	To identify the best performing peel ply to use with the peel ply method.
Time tests: 2-hour	Peel ply method	30-minute intervals up to 2 hours	Uncontaminated	To observe the influence that the time between removal of peel ply and application of adhesive bond has on the bonding shear stress.
8-day margin time test	Peel ply method	2-day intervals up to 8 days	Uncontaminated	To obtain more data over a longer period of time to observe the real effect of the degradation of the shear stress over time.
Peel ply batch contamination test	Peel ply method	None	Peel ply batch was contaminated by leaving it on the production floor for 7 days without covering	To observe the influence that a contaminated batch of peel ply has on the bonding performance.

3.2 Tests description

3.2.1 The Baseline test

The baseline test was a test where the hand sanding mechanical surface preparation method was used to prepare the test samples. The purpose of this test was to establish a baseline value for the bond strength to which the peel ply method can be compared to. The design allowable strength used in the sailplane industry is 7[MPa] (Schoberth, et al., 2017, p. 7) and it was expected that the baseline value will confirm this as a minimum value.

The specifications of this test were the following:

- Sandpaper grit – P120
- Sanding direction – One linear direction
- Surface finish – Dull, gloomy (Figure 3-1 provides an example of such a surface finish)
- Force applied during sanding – Small force. (This is one of the drawbacks of this method; each person applies a different force.)
- Solvent used – Acetone



Figure 3-1: Surface finish after sanding

3.2.2 Variety peel ply tests

Once the baseline value was determined the effect of the peel ply method could be investigated. As there are many different types and styles of peel plies on the market, a selection of which types to test had to be made. In this regard the experience of what the sailplane industry uses and what is commercially available and cost-effective was used. Five different types of peel ply were selected, and the bond performance of each compared. The peel ply types tested were Hexcell, I167, I086, I032, I126 (ECC). These are the standard codes of these peel plies obtained from AMT Composites. These different types of peel ply vary in material, weave and how it was manufactured. The data sheets of these peel plies can be found in the appendix.

3.2.3 Time tests: 2-hours

The next test involved the effect of elapsed time, between peel ply removal and bonding, on the bond performance. The test was done by bonding the specimens only after a specific time had elapsed after peel ply removal. Specimens were prepared at 30-minute intervals up to a maximum duration of 2 hours. After the peel ply was removed, the test specimens were stored in a closet covered with plastic to avoid dust contamination. This, however, allowed oxidation of the chemically active surface, which might affect the bond performance.

3.2.4 Time tests: 8-days

In this test, the time period was increased to 8 days with a 2-day sample interval.

3.2.5 Peel ply batch contamination test:

Due to the dusty nature of a composite workshop, there is a chance that the peel ply might be contaminated with carbon and glass fibre dust before used. The last test was therefore done to investigate the effect of dust contamination of the peel ply on the bond performance.

In this test, a batch of test specimens was prepared with the peel ply method with a new batch of peel ply. The same batch of peel ply was then left in an active composite workshop for 7 days. This allowed to peel ply to get contaminated with dust. The type of dust to what the peel ply was exposed to was mainly carbon or glass fibre dust, due to sanding and trimming of components manufactured from carbon or glass fibres. The contaminated peel ply was then used to prepare a batch of test specimens.

The two batches of test specimens, one prepared with a new batch of peel ply and the other with a contaminated batch of peel ply, were tested with the lap shear test. The results were then