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Investigation into different joining technologies for CFRP components

MAJOR PROJECT

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'This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.'

Signed:

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Abbreviations

ASTM	American Society for Testing and Materials
CFRP	Carbon Fibre Reinforced Plastic
DIC	Digital Image Correlator
FEA	Finite Element Analysis
FRP	Fibre Reinforced Plastic
GSM	Grammes
IPA	International Organization for Standardization
ISO	Isopropanol
JLR	Jaguar Land Rover
KN	Kilo Newton
LBADSA	Low-Bond Axisymmetric Drop Shape Analysis
MBI	Manufacturing Build Instruction
Mpa	MegaPascal
SB	Shot Blasted
SHB	Split Hopkinson Bar
SOP	Standard Operating Procedure
UD	Uni Directional
UWTSD	University of Wales Trinity Saint David
VB	Vapour Blasted

1 Acknowledgements

This project has been done in partnership with Lentus Composites.

Lentus Composites is an engineering led manufacturer of composite products, assemblies and systems for a range of industry sectors. Lentus can design, analyse, produce prototypes, carry out qualification testing and put parts into low or high-volume production. (Lentus Composites, 2020)

A big thank you goes toward the entire moulded department at Lentus Composites for the help and use of their facilities. Thank you to Nolan Richmond for giving me the opportunity to work in partnership with Lentus for this project and to Phil Kneeshaw for his time, help and effort for moving the project forwards.

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2 Abstract

The scope of this project was to investigate different joining technologies and surface treatments to improve bonding strength for current engineering projects at Lentus Composites.

The project initially evaluated the use of rivets in composite materials, then moved on to a hybrid of adhesive and rivets and finally the use of only adhesive with different surface treatments.

The surface treatments investigated were shot blasting, vapour blasting and plasma treatment. Shot Blasting and Vapour Blasting are readily available at Lentus Composites, on the other hand Plasma treatment was done at Enercon.

The manufacture of the coupons was done at Lentus, all coupons were made out of carbon fibre and cut into two different shapes a larger coupon was made for the riveted specimens, while a smaller coupon was made for the bonded specimens.

The coupons were tested at Lentus on a tensile test rig, loaded into jaws that clamp to both faces of the coupon and mount into carriers that bolt into the rig.

The tensile tests showed that the bonded coupons are stronger than riveted coupons. They also showed the inconsistency of the plasma treated coupons and the manufacturing faults liable from the production of the plasma treated coupons.

3 Introduction

The following paper investigates the different joining technologies available for carbon fibre composite materials. The first section of this paper investigates riveting and a hybrid ,adhesive and riveted joining mechanism, riveting is widely used in the automotive sector, it is a fast and precise way of joining two components, while the second part of this paper investigates plasma surface treatment of composite materials and how it compares with more traditional methods such as shot blasting and vapour blasting in the adhesive process.

Plasma treatment is a technology in fast development, it is widely used in the automotive sector but there is a lack of research into the effects of plasma on carbon fibre composites and how it affects the ultimate tensile strength of a bonded joint.

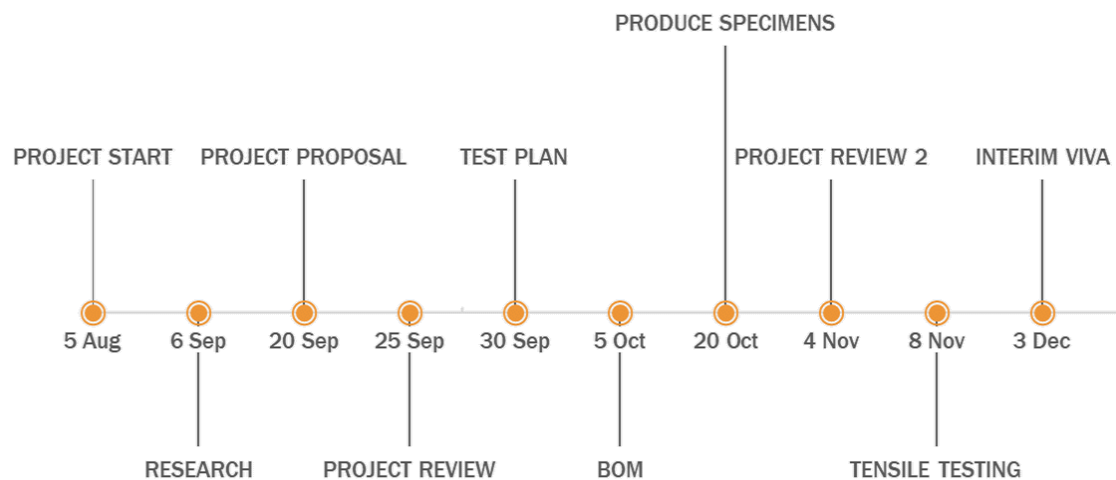
If it can be proved that plasma works just as well or better than traditional methods such as shot blasting, vapour blasting or hand abrasion, an automated production line can be greatly increased in efficiency thanks to the lower time it takes to treat a component before adhesion.

All components are tensile tested and analysed before and after, best efforts where done to standardise the whole procedure for accurate results.

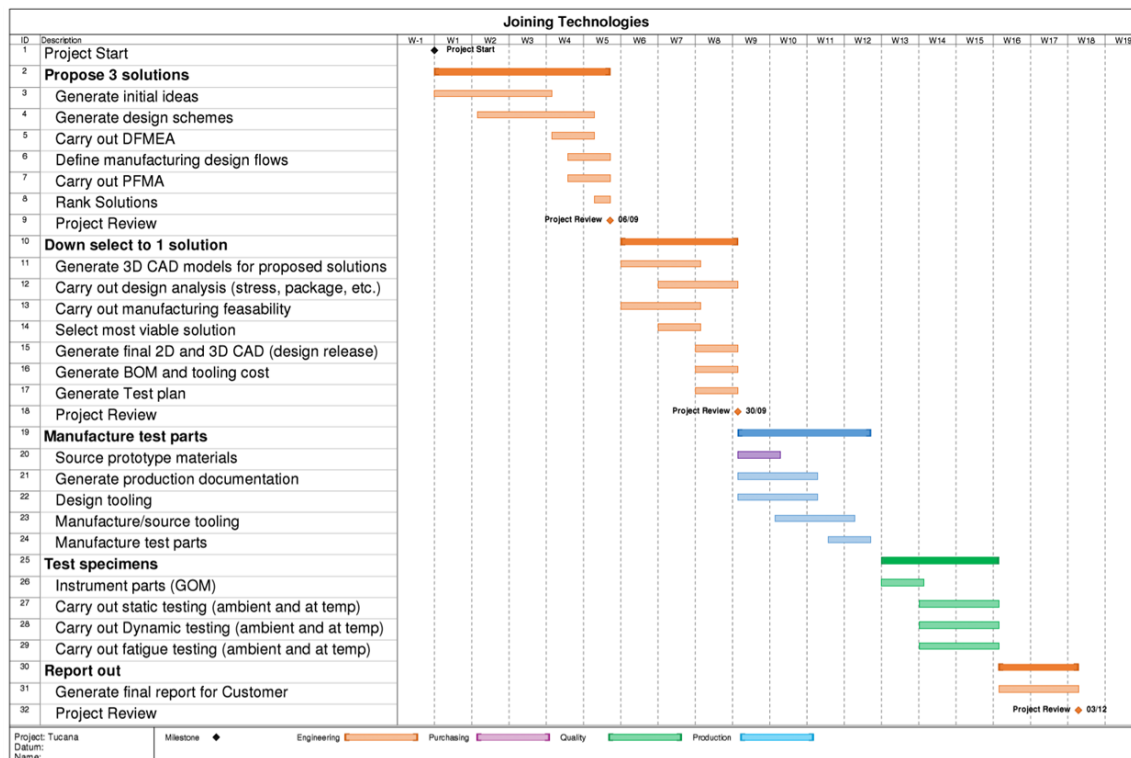
4 Project Management

The project was separated into two halves, August 2019 to December 2019 and January 2020 to May 2020. The first half consisted of an investigation into riveted joints and how they work on composite materials. The second half investigated different surface treatments in adhesively bonded composite materials.

4.1 Riveted joints, August 2019 to December 2019



Graph 1 –First half of project August 2019 to December 2019



Graph 2 – Gantt Chart of first half of project August 2019 to December 2019

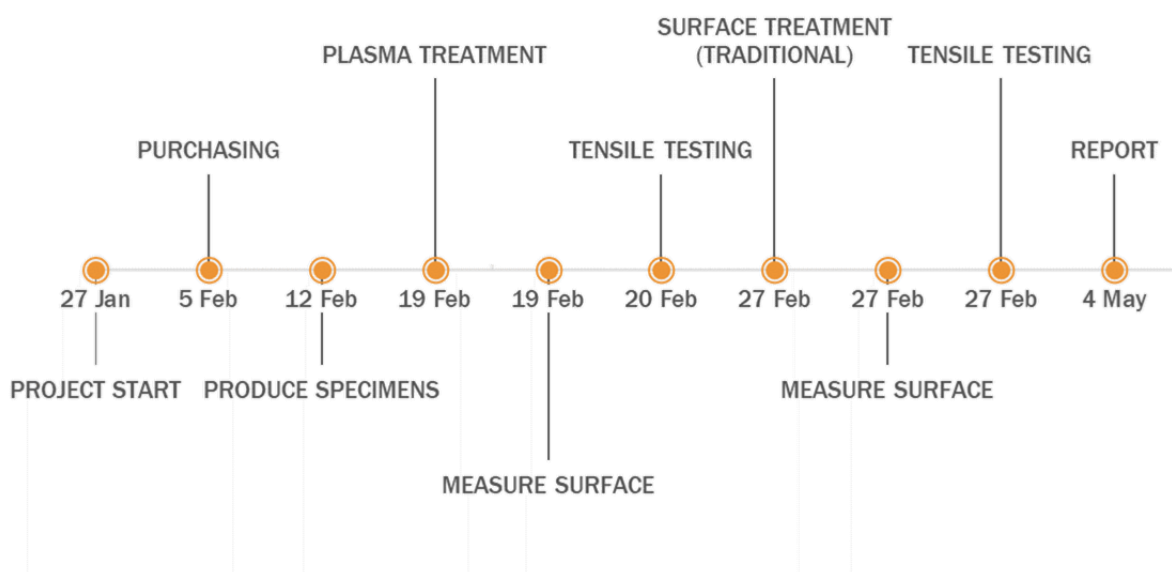
Due to the sizing of the Gantt Chart in Graph 2 a more detailed view of such chart can be seen in Appendix A, under Figure A-1.

Looking at Graph 1, the months of August and September were used for research and preparing what kind of specimens would be used and presenting a test plan to Lentus. The months of October and November were spent producing specimens and tensile testing.

Meetings between Lentus Composites, Jaguar Land Rover and the student were done.

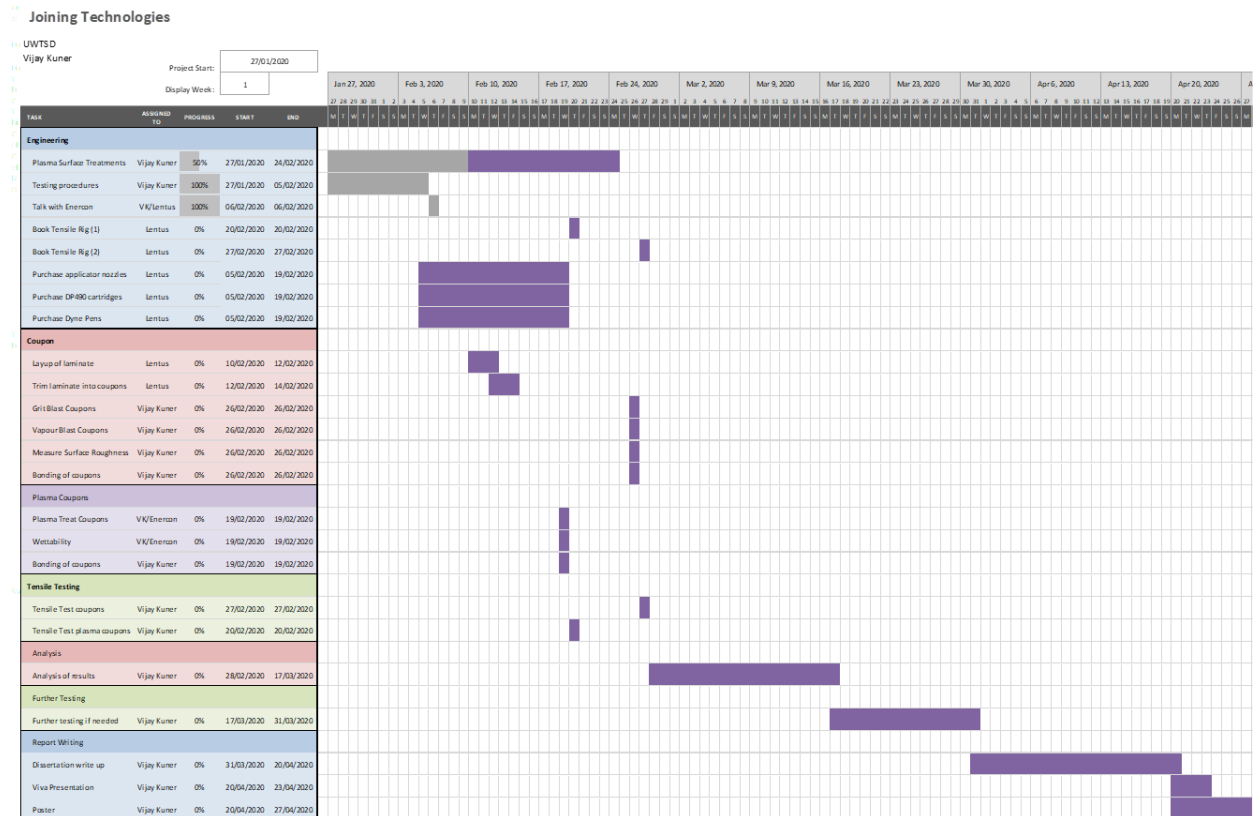
4.2 Bonded Joints, January 2020 – May 2020

Initially the project was going to look at different joining mechanisms for CFRP components on an automotive production line in collaboration with Jaguar Land Rover, but due to the nature of the project it was decided that a change in objective was needed. Therefore, the second half of the project consisted in investigating different surface treatments for CFRP and how they compare to each other, by conducting tensile testing.



Graph 3 – Second half of project January 2020 to May 2020

Looking at Graph 3, the month of January was used to prepare all the necessary materials and other tools such as dyne pens, for them to be ready for the month of February where the first batch of testing was done with plasma treated coupons, which were then tensile tested. At the end of the month of February the “traditional” (shot blasted and vapour blasted) surface treated coupons were tested. The months of March and April were used for analysis and write up of the project.



Graph 4 – Gantt Chart of second half of project January 2020 to May 2020

A more detailed view of Graph 4 can be seen in Appendix A, under Figure A-3

Graph 4 was done in excel and not in Microsoft Project due to licensing restrictions in UWTSD.

4.3 Production Management

For the good flow in the production of specimens, engineering drawings, MBI and SOP were produced by the student to mitigate any problems during production.

These documents were used by the production staff and the student to achieve standardisation of all specimens produced.

5 Literature Review

The background research of this paper talks about the following subjects:

1. **Fibre Reinforced Plastics (FRP).**
2. **Layup of composite materials.**
3. **Riveting composite materials.**
4. **Plasma Treatment of materials.**
5. **Testing Methods**
6. **Static and Dynamic Testing**

5.1 Fibre Reinforced Plastics

A Composite is a material formed of strong continuous or non-continuous fibres, surrounded by a weaker matrix. The matrix serves to distribute the fibres and to transmit the load to the fibres. (Gay, 2015)

A fibre is made from thousands of filaments with an average of 5 and 15 microns in diameter. There are two main types of fibre form:

- **Short Fibres**, these are a few centimetres in length and are mainly used in injection moulding.
- **Long Fibres**, these are cut to length at time of manufacturing a component, they are used in pre-preg.

Matrix materials which can be used are the following:

- **Polymeric matrix:** thermoplastic resins and thermoset resins. For this paper a thermoset resin based prepreg is used.
- **Mineral matrix:** silicon carbide, carbon. These are used for high temperature applications.
- **Metallic matrix:** aluminium alloys, titanium alloys, oriented eutectics.

The composite material used in this paper is a 2x2 Twill Carbon Fibre prepreg with an epoxy-based matrix; this is a woven fabric.

A woven fabric is composed of fibres oriented along two perpendicular directions: these directions are called either warp or weft (also can be named fill). The fibres are woven together, this means that the weft fibres pass over and under the warp yarns, following a pattern. There are different type of patterns which achieve different results as explained next:

- **Plain Weave:** The tows are woven in an over and under pattern. The short space between interlaces give the plain weave a high level of stability. Fabrics stability is how well the fabric holds its weave angle and fibre orientation. Due to this high level of stability this kind of fabric is not suitable for layups with complex contours. They are usually used for flat sheets, tubes and 2D curves. Another issue with this pattern is its harsh crimp (angle which the fibres make when woven) in the tows due to the short distance between interlaces. This harsh crimp can produce stress concentrations which can weaken the component over time. (Latteier, 2019) (ACP Composites, 2012)

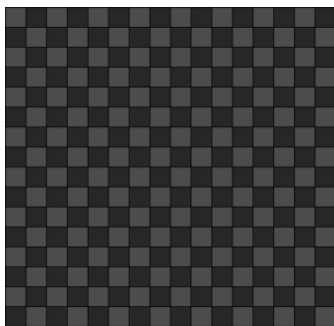
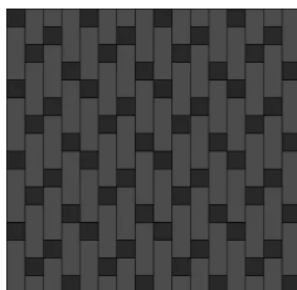
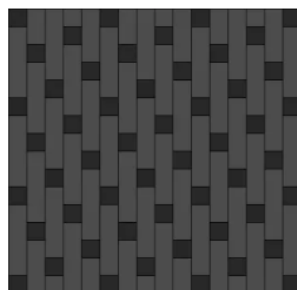


Figure 1 – Plain Weave (Latteier, 2019)

- **Satin Weave:** Its very good draping qualities mean it can easily form and wrap around complex contours. On the other hand, due to its high drapability, its stability is very low. Common satin weaves are four harness satin (4HS), five harness satin (5HS) and eight harness satin (8HS). The higher the satin weave, the more formability increases while stability decreases. The number in the Harness Satin names indicate the total number of tows passed over then under. For example, for 4HS, it passes over three tows then under 1. For 5HS, it passes over 4 then under 1. (Latteier, 2019) (ACP Composites, 2012)



4HS



5HS



8HS

Figure 2 – Satin Weave (Latteier, 2019)

- **Twill Weave:** Twill is kind of a hybrid between Satin and Plain weave. It has a good pliability around complex contours. It is better at keeping fabric stability than satin weave, but not as

well as plain weave. A tow strand in a twill weave passes over a set number of tows before it goes under the same amount of tows. The over and under pattern creates a diagonal arrowhead look, known as twill line. The larger distance between tow interlaces means fewer crimps compared to a plain weave and less potential stress concentrations. (Latteier, 2019) (ACP Composites, 2012)

- **2X2 Twill:** This kind of weave is the most used in industry, it has moderate formability and moderate stability. As the name implies, each tow passes over two tows and then under two tows. (Latteier, 2019) (ACP Composites, 2012)

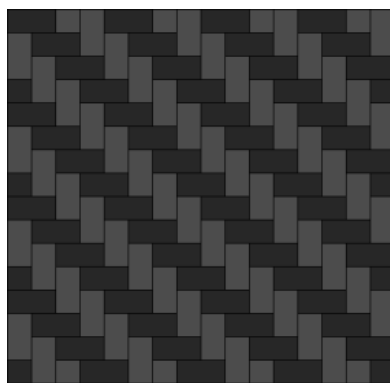


Figure 3 – 2X2 Twill (Latteier, 2019)

- **Unidirectional:** This is not a woven fabric. This kind of fabric has all its fibres in the same orientation. With this kind of fabric the engineer can pick the precise direction the fibres are to be placed and in this way the ideal strength can be achieved. A major drawback with this kind of fabric is its workability. It tends to fall apart very easily during layup as it has no interlacing fibres to hold it together. Usually when UD is used for a layup, the first and last layers are comprised of some sort of woven fabric. (Latteier, 2019)

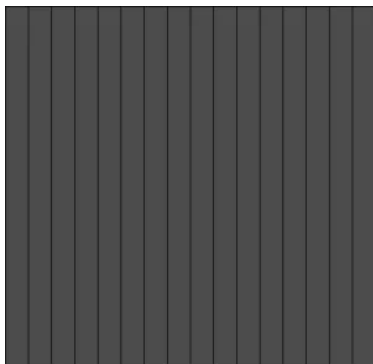


Figure 4 – Unidirectional (Latteier, 2019)

5.2 Layup of composite materials

Fibre Direction in a composite laminate affects the final component greatly, fibre direction is of utmost importance when trying to produce a strong laminate.

A quasi isotropic laminate results when the individual lamina is oriented in such a manner as to produce an isotropic matrix. There are several rules that apply to quasi isotropic laminates:

1. The total number of layers must be 3 or more.
2. All layers must have identical orthotropic elastic constants and identical thickness.
3. The orientation of the kth layer of an n-layer laminate is

$$\theta_k = \frac{\pi(k-1)}{n}$$

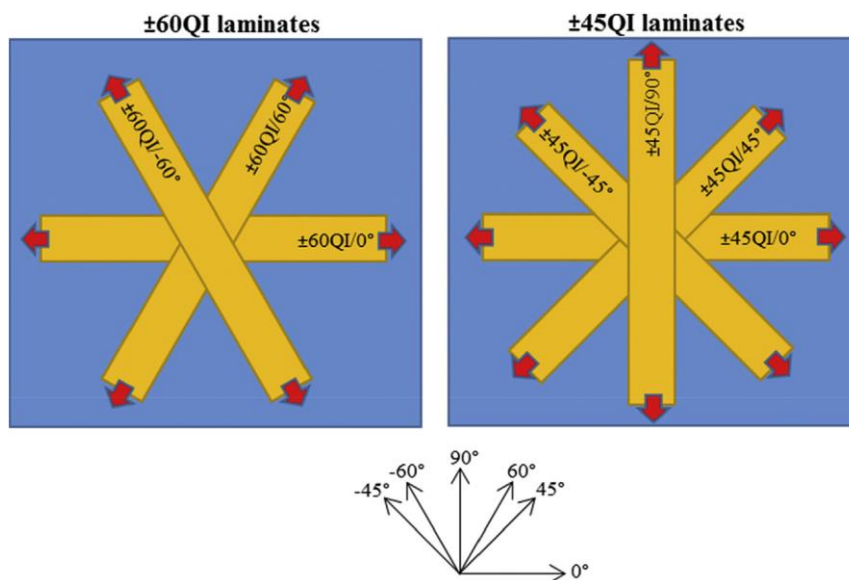


Figure 5 – Fibre Direction (Wisnom, 2017)

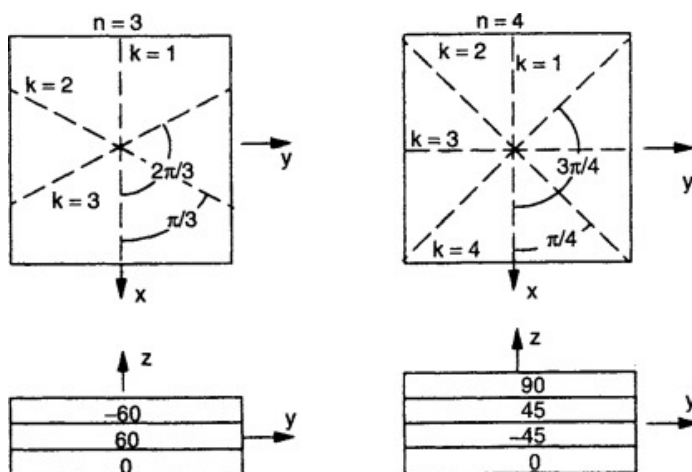


Figure 6 – Fibre Direction (Staab, 1999)

5.3 Riveting Composite Materials

In engineering, the riveting of two components together is common practice. In the field of composite materials, the riveting of, for example, two panels of carbon fibre can be counterproductive. On one hand, riveting is a quick and reliable process which gives the component consistent results, while on the other hand machining holes into a composite material for riveting can produce damages to the material such as delamination (separation of layers) or fibre protrusion (non – cut fibres). Those damages weaken the structure and create high stress concentrations around that area of the component. (Heberger, et al., 2016)

A paper by Lukas Heberger (Heberger, et al., 2016) studied the effect of three different manufacturing methods: conventional drilling, industrial state of the art drilling and circular milling. Out of the three, circular milling had the smallest variation in the cylindricity and the lowest delamination and fibre protrusion. For this project, due to manufacturing capabilities, conventional drilling was used for the holes.

Currently Lentus Composites are using rivets in a handful of projects. The riveting process used is manually done with a handheld rivet gun. Jaguar Land Rover currently use rivets in the production of their vehicles. Depending on the type of material used and the specific loads which the vehicle must withstand, different type of rivets are used. For example, with a high strength steel part to an aluminium part a harder rivet type would have to be used with a higher insertion pressure, than if it was an all-aluminium structure (Automotive Manufacturing Solutions, 2010)

Jaguar Land Rover decided to use riveting instead of spot welding due to the robustness of the rivets in comparison to the welding. It was found that for a large F-segment of a vehicle, on average between five and six thousand spot welds were used, while on average about three thousand rivets were required if the riveting process was implemented. Also, riveting required less infrastructure to be installed on the production line in comparison to spot welding, as well as having a lower carbon footprint. (Automotive Manufacturing Solutions, 2010)

5.4 Plasma Treatment of composite materials

This treatment aims to remove contaminants from the surface of the material, eliminate weakly bonded carbon planes, increase the roughness and/or attach chemically active groups to their surface. (Corujeira-Gallo & Dong, 2016)

It has also been proven that isopropanol post plasma treatment has a better average adhesion than unrinsed samples. This rinse post treatment removes the thin layer of ash from the plasma treated surface. (Morgan, et al., 2011). In this project, the use of isopropanol after plasma treating a component defeats the point of usage of plasma, which is to cut production time.

5.4.1 Surface Chemistry

The chemistry of a surface affects its surface energy and wettability. Polar elements, such as oxygen and nitrogen, are removed from CFRP during the manufacturing process of CFRP, more precisely the high temperature carbonisation under inert gas. Therefore, to counter this loss in surface energy, plasma treatments are used. (Corujeira-Gallo & Dong, 2016)

The longer the plasma is bombarding the material surface, the more roughness of the material increases, but the material becomes weaker.

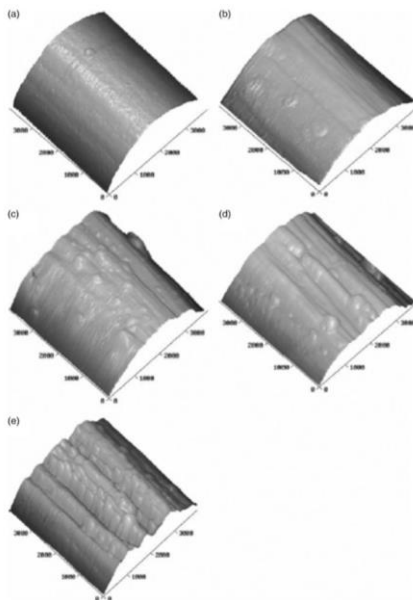


Figure 7 – Surface profile of carbon fibres after plasma treatment with increasing time: a) untreated, b) 5min, c) 10min, d) 15min and e) 20min

In this project the treatment of the specimens was in terms of seconds to avoid the weakening of the material and to increase production efficiency timewise.

5.4.2 Surface Free Energy

The term Surface Free Energy refers to the excess energy that the surface has compared to the bulk of the material. (Lauren, 2018)

The Surface Free Energy is the surface tension of a solid. This energy can be calculated with contact angle measurements. The Surface Free Energy is the quantitative measure of the intermolecular forces at the surface, which is independent of the liquid used. In this project water and n-octane are used to calculate the contact angles. Dyne pens are also used to give an approximate value of the Surface Free Energy. (Lauren, 2018)

Cohesive forces between molecules in a liquid are shared with all neighbouring atoms. Those on the surface have no neighbouring atoms above and exhibit higher attractive forces upon their nearest neighbours on the surface. This enhancement in the intermolecular attractive forces at the surface is called surface tension. Figure 8 shows a graphic with the molecules on top creating surface tension and the ones below sharing energy. (Georgia State University, 2016)

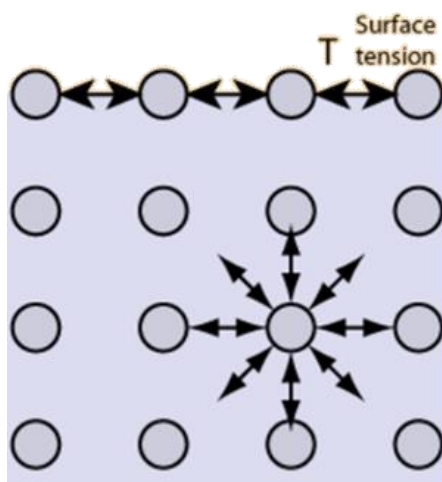


Figure 8- How molecules react between each other creating surface tension (Georgia State University, 2016)

Surface tension is measured in dynes/cm, the force in dynes to break a film of length 1 cm. (Georgia State University, 2016)

Solid – liquid interactions are determined by the surface free energy of the solid and the surface tension of the liquid. High surface free energy materials are those where it is easily wetted by a liquid. An example of a high surface free energy material is glass. On the other hand, a low surface energy material is polypropylene and in the case of this project Carbon Fibre. To increase the surface energy of these materials, surface treatments are necessary. (Lauren, 2018)

5.4.3 Wettability

Wettability is the degree to which a solid is wetted by a liquid, measured by the force of adhesion between the solid and liquid phases. Complete wetting is defined as spreading. Spreading happens either on very low surface tension liquids or high surface free energy solids. (Websters New World, 2010) (KRUSS, 2020)

The wettability is measured by the contact angle. This is the angle between the surface of the liquid and the outline of the contact surface. (KRUSS, 2020) Figure 9 shows the difference between complete wetting and bad wetting, the smaller the contact angle the better wetting the component has.

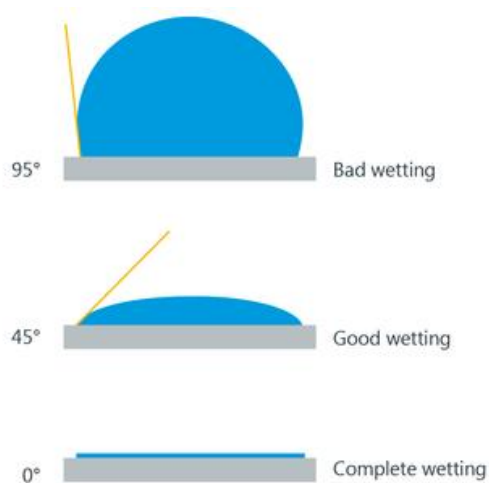


Figure 9 – Differences between good and bad wetting (KRUSS, 2020)

An example of reduction of wettability is when a user waxes their car to prevent the water from spreading. On the other hand, a good wetting is needed when using adhesives as this implies that there are good adhesive forces between the two materials.

Adhesion is the interaction between unlike molecules, while cohesion is the interaction between same molecules. For example, when a drop of water is placed on a material it beads up, while a drop of ethanol spreads. This happens because in the water there are strong cohesive forces named hydrogen bonds that pull the molecules towards each other. Ethanol, on the other hand, has weak cohesive forces called van der Waals forces. This causes ethanol to spread more easily on solid forces. (Lauren S. , 2019)

High energy solids have very strong chemical bonds. This gives the surface a very high energy, which translates to very good wetting. Other solids are classed as low energy, for example Teflon. (Lauren S. , 2019)

5.4.4 Polarity and dispersity.

Polar interactions are caused by permanent and localisable asymmetry of electron density in molecules. Water has a strong polarity, which in turn means it has a high Surface Free Tension. A solid surface with a high polarity is glass. (KRUSS, 2020)

Disperse interactions are caused by statistical fluctuations of the electron density distribution in a molecule, which cause temporary charge differences at different locations. Electrostatic attraction happens between molecules. For example, Polyethylene forms dispersive interactions. These interactions affect the wettability of water with these kinds of surfaces. Plasma treatment increases the polar fraction of Surface Free Energy and makes the plastic more like the water. (KRUSS, 2020)

The combination of both polar and dispersive interactions: the Surface Free Energy can be calculated using contact angles. Fowkes theorem is used to calculate the Surface Free Energy with the use of polar and dispersive interactions. This is further explained later in the paper. (KRUSS, 2020)

Figure 9 shows the wetting and adhesion depending on the polar and disperse fractions. The big hands symbolise polar, the small represent disperse interactions. In the upper picture, the interactions are identical, resulting in maximum adhesion and a contact angle of 0° . Below is an example with non-identical interaction components. For the specimens in the project, the lower the contact angle the better the adhesion of the two materials.

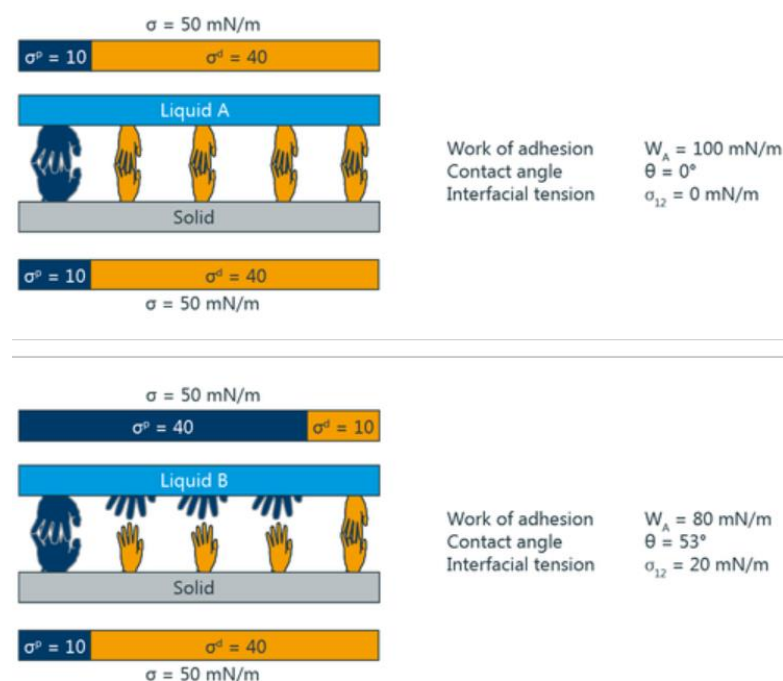


Figure 10 – Wetting and adhesion comparison with different results (KRUSS, 2020)

5.5 Testing Methods

These are testing methods that have been done before at Lentus.

To be able to gather true data from the test samples produced, testing of the specimens was done. Standard test methods produced by ISO (International Standards Organisation) or by ASTM (American Society for Testing and Materials), were used to follow an organised and internationally accepted test method.

Coupon testing was used to characterise and validate basic performance attributes of the connection. Tests were conducted on both the new composite concept and on an equivalent metallic geometry manufactured using current production representative technology. By comparing the new connection technology with existing metallic parts, a meaningful back-to-back comparison could be made. The coupons were made with composite materials with alternative ply orientations for comparison and to achieve the strongest laminate and best dissipation of stress concentrations around the filled hole (riveted hole)

Straight Coupon

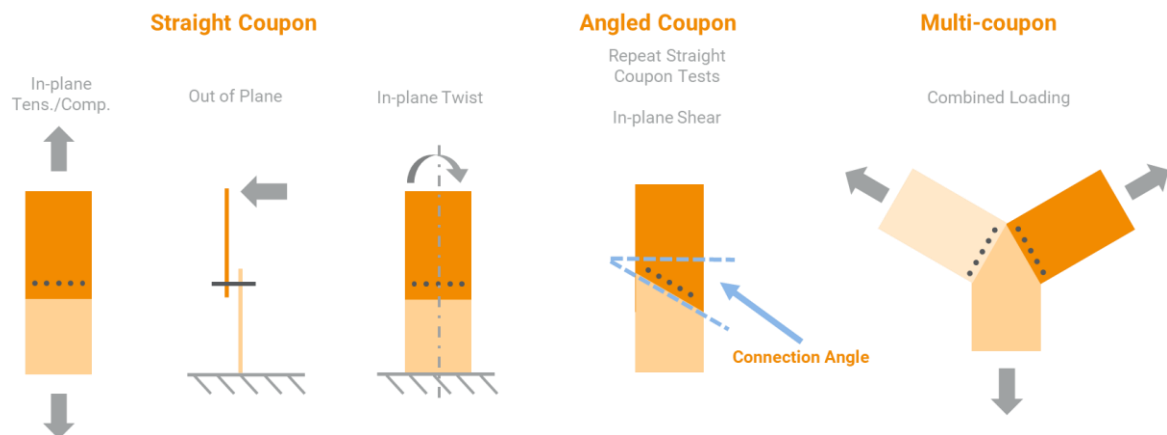
Straight coupons provided information on the basic tensile, compressive and torsional properties of the connection. In-plane and out of plane samples were tested on uniaxial test rigs, in-plane twist testing were performed on a torque test rig. This equipment was available on site at Lentus. New fixturing consisting of simple metallic fabrications were designed and built by Lentus. Coupons were subjected to stiffness, fatigue and ultimate strength testing. Initial tests were performed at room temperature, later testing may be performed at elevated or reduced temperature by enclosing fixtures in an environmental chamber.

Angled Coupon

Angled coupons provide information on the shear properties of the connection. By varying the angle of the coupon connection between 0° and 45° the effects of pure tension, pure shear and combined loading could be investigated with the same test fixturing and methods. Angled coupons were subjected to the same suit of testing as straight coupons.

Multi-coupon

Multi-coupons provide information on more complex combined axes and load inputs. Multi-coupon samples were tested using JLR's existing test equipment.



5.5.1 Digital Image Correlation

Lentus has the in-house capability to perform real-time full-field non-contact strain measurement testing using GOM Aramis DIC equipment. This measurement technology is especially useful when testing components with highly localised stiffness variation, such as found in the UD reinforced coupons. Using DIC inspection allowed achieved press fit strains in service deflections to be directly measured in fine detail. DIC inspection data can be compared directly with FEA predicted strains to validate modelling assumptions.

It consists of two cameras, which are pointed at the objective. These two cameras are capable of measuring 3D displacements and 3D surface strain. A speckled pattern was painted on to the component and the DIC was capable of tracking the specks on a white background and measuring the displacement of such specks.

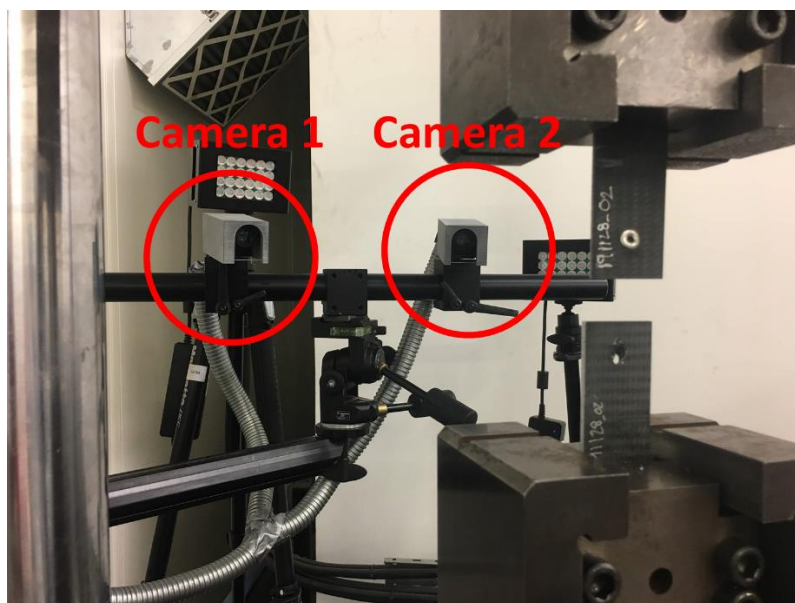


Figure 11 – Digital Image Correlator Setup

5.5.2 Bearing/bypass interaction:

Each individual fastener transfers a bearing load on the laminate around the hole, but the remaining load bypasses this fastener to act on the next fastener in line (Adams, 2011).

ASTM D7248 was used to calculate this bearing bypass on double jointed specimens.

5.5.3 Bearing Testing Method

Several test methods can be undertaken to calculate the forces on the laminate and filled hole geometry.

ASTM D5961/D5961M – 1:

This test method covers the bearing response of pinned or fastened joints using multi directional polymer matrix composite laminates reinforced by high modulus fibres by double-shear tensile loading (Procedure A), single shear tensile or compressive loading of a two piece specimen (Procedure B), single shear tensile loading of a one piece specimen (Procedure C), or a double shear compressive loading (Procedure D). (ASTM, 2013)

- Summary of test **method A, Double Shear, Tension:**

A flat rectangular coupon, with a centreline hole located near the end of the specimen. The bearing force is usually applied through a close tolerance. The bearing is created by loading the assembly in tension in a testing machine. (ASTM, 2013)

Both the applied force and the associated deformation of the hole are monitored via a DIC (Digital Image Correlation) system. The specimen is loaded till a maximum load is achieved; the test is terminated at a point before the true data is masked by extreme deformations of the hole.

Bearing stress versus bearing strain is plotted for the entire process and failure mode noted.

- Summary of test **method B, Single Shear, Two Piece Specimen:**

Two rectangular test specimens fastened together by two centreline holes located near the end of each specimen. Some doublers are used on each end of the specimens so when the specimens are placed on the tensile rig, the holes are going down the centreline.

Hydraulic grips are used to grip the fastened specimen from the ends and placed under load.

A support structure can be used to stabilise the test, in this case the load goes through the structure before the specimen. This kind of structure is usually used for compressive loads but can be also used for tensile loads.

Both the applied forces and deformations are monitored via a DIC system. The hole deformation is normalized with the hole diameter to achieve an effective bearing strain. Furthermore, the applied force is normalised by the projected hole area to achieve an effective bearing strain.

The ultimate bearing strength of the material is determined from the maximum force carried prior to test termination.

- Summary of test **method C, Single Shear, One Piece Specimen:**

A flat rectangular specimen is produced with a hole down the centreline on one of its ends. The specimen is put under load with a fixture, through a fastener with a close tolerance, lightly torqued that is reacted in single shear.

- Summary of test **method D, Double Shear, Compression:**

A flat rectangular specimen is produced with a hole down the centreline on one of its ends. The specimen is put under load with a fixture, through a fastener with a close tolerance, lightly torqued that is reacted in single shear. The bearing force is created by loading the assembly in compression in a testing machine.

The standard test configuration for this procedure does not allow any variation of any of the major test parameters, other than overall specimen length.

Comparison of test procedures:

Test methods A and D are particularly useful for basic material evaluation and comparison.

Test methods B and C, are useful for specific evaluation of joint configurations, including fastener failure modes.

Test method B can be undertaken in a supported or unsupported way. Supported is ideal for compressive testing, while unsupported is for tensile testing.

Procedure C is especially effective for countersunk fastener bearing strength data where a near double shear fastener rotational stiffness is desired.

Procedure B and C have been extensively used in the development of design allowable data.

Factors that influence the testing:

General:

Material properties, material preparation and lay-up, specimen stacking sequence, specimen preparation, specimen conditioning, environment of testing, specimen alignment and gripping, speed of testing, time at temperature, void content, and volume percent reinforcement.

Specific:

Edge distance ratio, width to diameter ratio, diameter to thickness ratio, fastener type, fastener shear strength, fastener torque, fastener or pin material, fastener or pin clearance, tensile or compressive loading, countersink angle and depth of countersink, type of grommet, type of mating material, number of fasteners, and type of support fixture.

Properties obtained:

- Ultimate bearing strength, of the composite laminate or laminate-fastener joint.
- Offset bearing strength, of the composite laminate or laminate-fastener joint.
- Bearing stress/bearing strain curve.

Test Method B was followed for this project, as seen in Figure 12 and Figure 13.

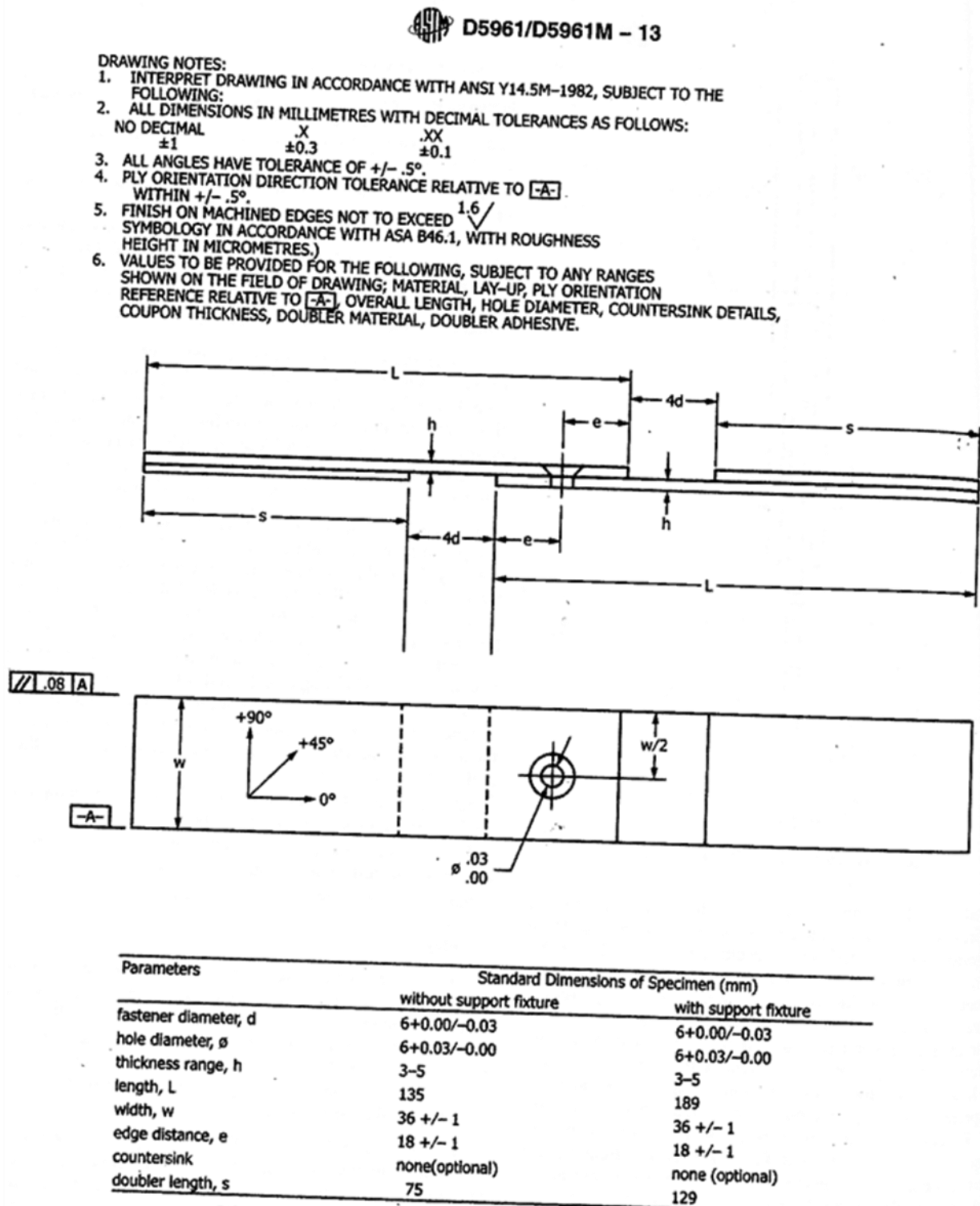


FIG. 5 Single-Shear, Two-Piece Single-Fastener Test Specimen Drawing (SI)

Figure 12 – ASTM D5961 – Testing Method B – Single Shear Two Piece Test Specimen Drawing (ASTM, 2013)

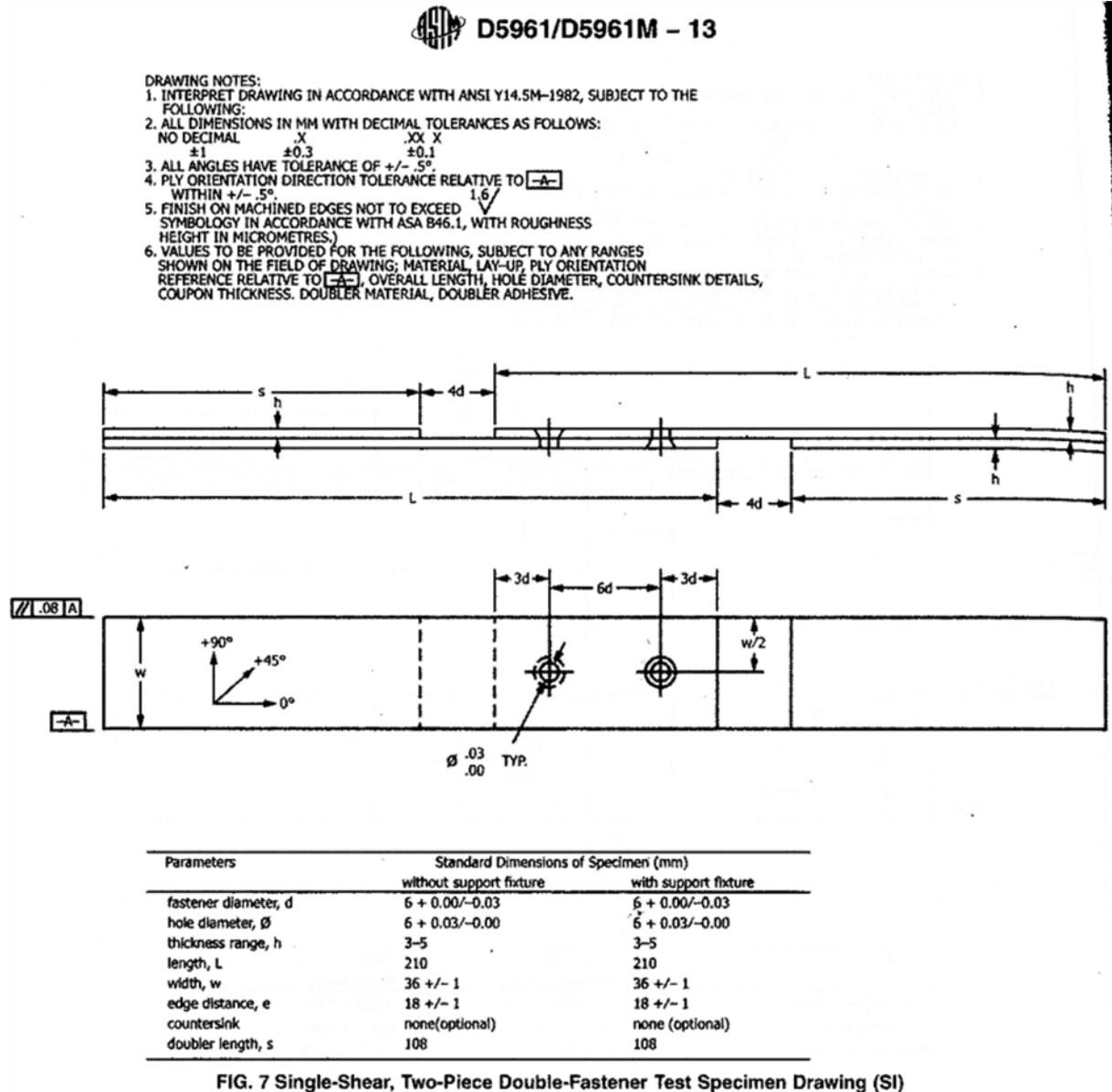


Figure 13 – ASTM D5961 – Testing Method B – Two Piece Double Fastener Test Specimen (ASTM, 2013)

5.5.4 Adhesive Testing Method

For the adhesive testing ASTM D5868 was followed, this standard, in comparison to the riveted method from the previous section, allows the user to use smaller sized specimens. Carbon fibre being a valuable material, the user changed the size of the specimen to ASTM D5868 specification to save material. For comparison between riveted joints and bonded joints the shear stress was calculated for both and compared. (ASTM, 2014)

This test method can be followed to bond CFRP to each other, as well as to bond metals.

Dimensions

CFRP were cut into coupons, 25.4mm by 101.6mm, at a nominal thickness of 2.5mm. In the case of using metal coupons the thickness of the metal was to be 1.5mm. Sharp edges are favourable. (ASTM, 2014)

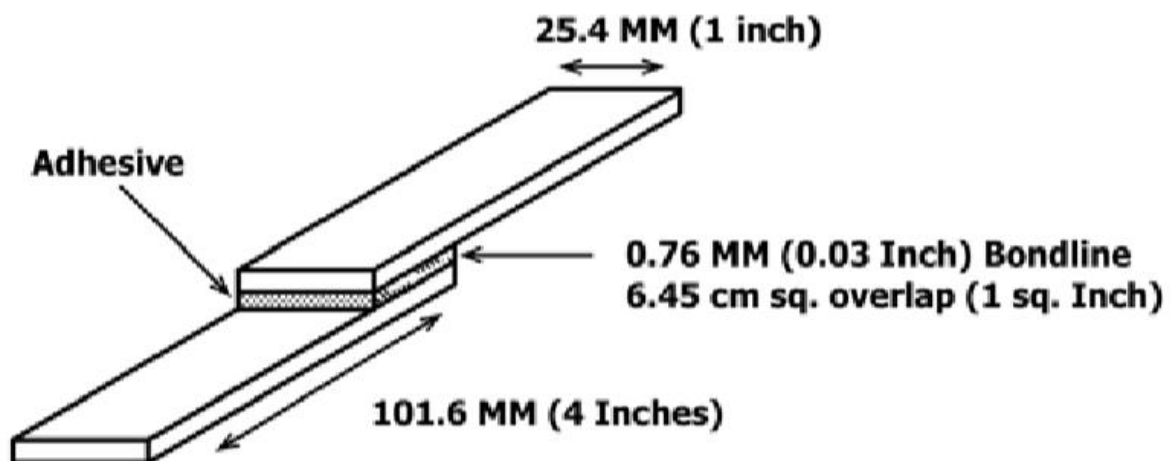


Figure 14 – ASTM D5868 Bonded Coupons dimensions

Bond Thickness

Bond thickness was controlled by means of a physical object, to achieve a 0.76mm adhesive bondline thickness. For this a jig was produced and used to control this thickness. (ASTM, 2014)

5.5.5 Wettability methods

For calculating the Surface Energy of a solid, the surface tension of the liquids used to calculate it must be known beforehand. The liquids used were water and n-octane. The method used in this paper for calculating the surface energy is the Fowkes theory, a two-component model. There are many different theories developed by researchers to calculate this energy, the most common ones are:

- **Zisman Theory:** the use of only one liquid which has a very high surface tension is used. This theory only works with non-polar surfaces such as polyethylene and polypropylene. If a surface is even slightly polar this theory must not be used. This is because it is a one parameter model. It ignores any specific liquid/solid interactions, which can happen with materials such as glass. (CR, 1999)
- **Owens/Wendt Theory:** this measures polar interactions between liquid and solid surfaces. This is a two-parameter model, as it uses polar and disperse interactions. It uses two fundamental equations - the Goods Equation and Youngs Equation. By combining both equations the Owens Wendt Equation can be found. By using the contact angle data measured and the surface tension measures, polar and dispersive, of the liquids the Surface Free Energy of the solid can be used. A drawback to this theory is that a minimum of seven liquids must be used. This theory is used on materials which are moderately polar, for example polymeric. (CR, 1999)
- **Van Oss Theory:** this separates the surface energy into three components, a dispersive component, an acid component and a base component. The polar component, from the previous theories, is divided into the acid component and the base component. (CR, 1999)

If the Fowkes theory is not a possibility the next best option that can be used with CFRP is the Owens/Wendt Theory.

Fowkes Theory

This theory is very similar to the Owens and Wendt Theory but only two liquids are necessary. In this case water and n-octane.

Fowkes theory is based on three fundamental equations:

1. Youngs Equation

$$\sigma_S = \sigma_{SL} + \sigma_L \cos \theta$$

Equation 1 – Youngs Equation (CR, 1999) (Jun, Hong-tao, De-yun, & Yu-xia, 2012)

Where, σ_S is the Surface Free Energy (Solid), σ_{SL} is the interfacial tension, σ_L is the tension of the liquid and θ is the contact angle.

2. Dupre's Definition of Adhesion Energy

$$I_{SL} = \sigma_S + \sigma_L - \sigma_{SL}$$

Equation 2 – Dupre's Equation (CR, 1999) (Jun, Hong-tao, De-yun, & Yu-xia, 2012)

Where, I_{SL} is the energy of adhesion per unit area between a liquid and a solid surface.

3. Fowkes Theory

Adhesive energy between a solid and liquid can be separated into interactions between the dispersive components and the two phases interactions between the polar components.

$$I_{SL} = 2 \left[(\sigma_L^D)^{1/2} (\sigma_S^D)^{1/2} + (\sigma_L^P)^{1/2} (\sigma_S^P)^{1/2} \right]$$

Equation 3 – Fowkes Equation (CR, 1999)

Where, σ_L^D is the dispersive component of the surface tension of the liquid, D for dispersive and L for liquid. σ_L^P is the polar component of the surface tension of the liquid, P for polar. σ_S^D is the dispersive component of the surface energy of the solid, S for solid. σ_S^P is the polar component of the surface energy of the solid.

The three equations, Youngs equation, Dupre's equation and Fowkes equation, are combined into one to give the main equation of Fowkes theory.

$$(\sigma_L^D)^{1/2} (\sigma_S^D)^{1/2} + (\sigma_L^P)^{1/2} (\sigma_S^P)^{1/2} = \frac{\sigma_L (\cos \theta + 1)}{2}$$

Equation 4 – Final Fowkes Equation (CR, 1999)

From this equation, by using a liquid with only dispersive values and no polar values, n-octane, the following equation can be calculated.

$$\sigma_S^D = \frac{\sigma_L (\cos \theta + 1)^2}{4}$$

Equation 5 – Non polar equation (CR, 1999)

Equation 5 has been simplified from equation 4, the contact angle of a non-polar liquid was used, n-octane, this means that $\sigma_L^P = 0$ and $\sigma_L^D = \sigma_L$, can be taken from known values in table 1.

Table 1 – Known values for liquids (CR, 1999)

Liquid	Room Temperature Surface Tension (mN/m)	Contact Angle on PTFE (degrees)	Dispersive Component (mN/m)	Polar Component (mN/m)
n-hexane	18.4	12.0	18.4	0.0
n-heptane	19.9	25.6	19.9	0.0
n-octane	21.3	33.0	21.3	0.0
n-decane	23.8	42.3	23.8	0.0
cyclohexane	25.5	47.1	25.5	0.0
n-tetradecane	26.4	49.4	26.4	0.0
toluene	28.4	58.2	26.1	2.3
nitromethane	36.5	84.8	22.0	14.5
methyl benzoate	37.2	79.3	27.0	10.2
benzyl alcohol	39.0	78.6	30.3	8.7
ethylene glycol	47.7	94.9	26.4	21.3
formamide	57.0	107.2	22.4	34.6
glycerol	63.4	100.7	37.0	26.4
water	72.8	113.7	26.4	46.4

Once the non-polar liquid is used, a second liquid with both dispersive values and polar values is used, water, with these values σ_S^P can be calculated as the only unknown in equation 4. Once that is calculated the overall surface energy of the solid can be calculated.

$$\sigma_S = \sigma_S^P + \sigma_S^D$$

Equation 6 – Overall Surface Energy of the solid (CR, 1999)

This theory has its basis on adhesion, as is the case of this paper.

5.6 Static and Dynamic Testing

5.6.1 Static Testing

Tensile testing of the material is performed in a conventional static testing machine. This kind of testing will determine the breaking point of the component and its elongation, called strain. (Hofer, 2020)

There are different types of conventional static testing machines:

- Constant load type: employ weights directly, both to apply load and to measure it. (Hofer, 2020)
- Constant load-rate: employ separate load and measurement units; load is applied by means of a hydraulic ram into which oil is pumped at a constant rate: this kind of testing machine is used for the tensile testing of the components used in this paper. (Hofer, 2020)
- Constant displacement-rate: machines driven by gear screws. (Hofer, 2020)

The test machine grips used in tensile testing are designed to spread the load evenly across the specimen without producing stress concentrations at its location. Non uniform loading causes bending of the specimen in addition to tension. Therefore, the jaws of the rig swivel in the linkage to try and mitigate this bending. (Hofer, 2020)

A problem in compression testing is that if the sample used has a large length it will be prone to buckle. To prevent this, the samples are kept short and stubby. (Hofer, 2020)



Figure 15 – Constant load-rate machine with grips on left, tensile tested coupon on right.

5.6.2 Dynamic Testing

One frequently used technique is the Split Hopkinson Bar (SHB). In this procedure a small specimen is placed between two aluminium bars, an incident bar and a transmitter bar. The specimen is loaded via a wave which is generated by the incident bar. Most of the energy produced by that wave is reflected back through the incident bar, while the rest goes through the specimen and exits through the transmitter bar (Amos Gilat, 2018). Tensile, compression and torsional testing can be done using different variations of the SHB technique. The Stress and Strain of the specimens are calculated by the waves in the bars which remain elastic during the test and collected by strain gauges set on the bars. The specimen during the compression test is simply placed between the two bars and it is held by its own accord once the test takes place. During the tensile and torque test the specimen has to be attached to the bars with some fixtures, this has an impact on the transmission of the waves from the bars to the specimen (Amos Gilat, 2018).

High Speed Cameras are used to track the deformations on the specimens while they are under load.

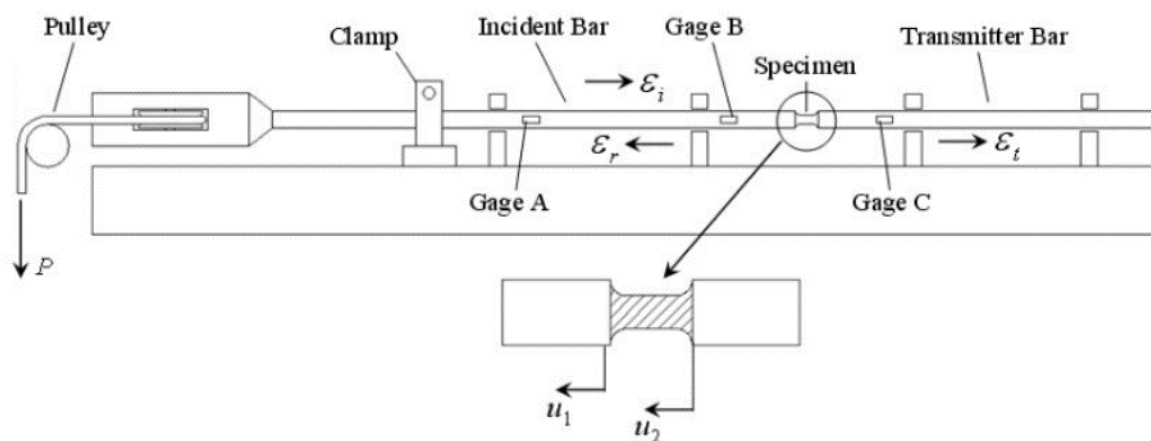


Figure 16 - Dynamic Compressive Testing of specimen (Amos Gilat, 2018)

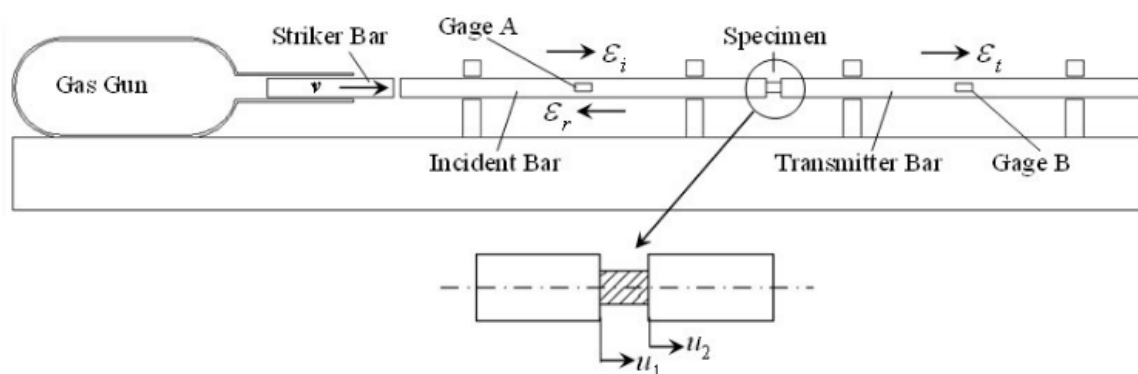


Figure 17 – Dynamic Compressive Testing of specimen (Amos Gilat, 2018)

Due to testing and time restrictions dynamic testing could not be done for this project.

6 Methodology

6.1 Material properties.

6.1.1 Carbon fibre material

The material used for producing the coupons is the following:

- HS0838 – CARBON 205 GSM 2X2 TWILL TR30S T 3K - 0/90°

With the following properties:

Table 2 – Carbon fibre properties (TENCATE, 2013)

HS0838 – CARBON 205 GSM 2X2 TWILL TR30S T 3K - 0/90° CONFIGURATION WOVEN LAMINATES

Property	Condition	Method	Results	
Tensile Strength (Warp)	RTD	ISO 527-4	595 MPa	86 ksi
Tensile Modulus (Warp)	RTD	ISO 527-4	56.1 GPa	8.1 Msi
Poisson's Ratio (Warp)	RTD	ISO 527-4	0.04	
Tensile Strength (Weft)	RTD	ISO 527-4	580 MPa	84 ksi
Tensile Modulus (Weft)	RTD	ISO 527-4	52.4 GPa	7.6 Msi
Poisson's Ratio (Weft)	RTD	ISO 527-4	0.04	
In Plane Shear Strength	RTD	EN 6031	112 MPa	16 ksi
In Plane Shear Modulus	RTD	EN 6031	3.57 GPa	0.5 Msi
Poisson's Ratio	RTD	EN 6031	0.8	
Compression Strength (Warp)	RTD	EN 2850	567 MPa	82 ksi
Compression Modulus (Warp)	RTD	EN 2850	52.5 GPa	7.6 Msi
Compression Strength (Weft)	RTD	EN 2850	563 MPa	82 ksi
Compression Modulus (Weft)	RTD	EN 2850	49.4 GPa	7.2 Msi
ILSS (Warp)	RTD	ISO 14130	68.1 MPa	10 ksi
ILSS (Weft)	RTD	ISO 14130	68.7 MPa	10 ksi

* Cured 1 hour at 120°C (248°F) at 50% Vf.

This material is the most used material at Lentus Composites and was readily available. Due to these factors it was chosen for use in this project.

It is a 2x2 twill pre-preg, with an epoxy matrix, commonly used in the composites sector.

6.1.2 Adhesive

An epoxy-based adhesive was used. It is important that the adhesive used for bonding two CFRP components has the same matrix component as, if it does not, the composite can create unwanted chemical reactions.

The adhesive used was DP490 manufactured by 3M, a cure cycle of 1 hour at 80°C was used according to the 3M DP490 Datasheet. (3M, 1996)

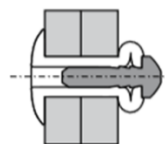
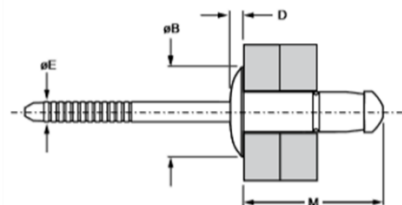
“DP490 is a black, thixotropic, gap filling two component epoxy adhesive with particularly good application characteristics. It is designed for use where toughness and high strength are required and shows special benefits in the construction of composite assemblies. The product has excellent heat and environmental resistance”. (3M, 1996)

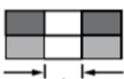
6.1.3 Rivet

4.8mm diameter Avinox BE61 Series, Stainless Steel rivets were used for the riveted specimens.

These were used, due to their availability at Lentus Composites, as these are what are currently used on the production line. They can withstand shear loads of 5.5KN. (Avdel, 2015)

Table 3 – Avinox BE61 Series, Stainless Steel Datasheet (Avdel, 2015)



ø					M	øB	D	øE		
nom.	min.	max.	min.	max.	max.	max.	max.	max.	kN ^{1) 2)}	kN ¹⁾
3.2 (1/8")	1.0	3.0	3.3	3.4	9.0	6.6	1.1	2.1	1.60	2.00
	3.0	5.0			11.5				1.70	
	5.0	7.0			14.1				3.20	
4.0 (5/32")	1.0	3.0	4.1	4.3	10.3	8.0	1.5	2.6	2.80	4.00
	3.0	5.0			12.9				5.20	
	5.0	7.0			15.6				5.20	
4.8 (3/16")	1.5	3.5	4.9	5.1	12.8	9.6	1.5	3.2	5.50	5.00
	3.5	6.0			15.4					
	6.0	8.5			18.4					
	7.0	10.0			19.9					

all dimensions in mm / en millimètre / alle Maße in mm / in millimetri / en milímetros



6.1.4 Tooling board

Epoxy tooling board was used to manufacture the bonding jig for the specimens. This jig controlled the adhesive bondline thickness.

Lentus has a lot of offcuts of tooling board, one of these offcuts was used.

6.2 Procedures for production and assembly of specimens

In any engineering company procedures must be put in place to guarantee the smooth operation of any project. In this case an MBI (Manufacturing Build Instruction), SOP (Standard Operating Procedure) and travellers were created. These can be seen in their raw form in Appendix B.

6.2.1 Carbon Fibre Layup and cutting procedure

The following procedure was followed to produce flat plates of carbon fibre which were cut to size on a band saw to achieve the desired sized specimen of 25.4mm x 101.6mm.

1. **Seal and release** steel plates: before layup of carbon fibre, a layer of sealing liquid was placed over the steel plates before the release liquid. The release liquid, as the name implies, makes sure the carbon fibre does not stick to the steel plate.
2. **Layup**: the layup in Table 4 was followed to achieve a thickness close to 2.5mm. Finished layup can be seen in Figure 18.

Table 4 – Layup of Carbon Fibre Flat Sheet.

LAY UP					
PLY	MATERIAL	WEIGHT	RESIN	ORIENTATION	THICKNESS
1	CARBON	205	E722	0°	2.65
2	CARBON	205	E722	±45°	
3	CARBON	205	E722	90°	
4	CARBON	205	E722	±45°	
5	CARBON	205	E722	0°	
6	CARBON	205	E722	±45°	
7	CARBON	205	E722	90°	
8	CARBON	205	E722	±45°	
9	CARBON	205	E722	0°	
10	CARBON	205	E722	±45°	
11	CARBON	205	E722	90°	
12	CARBON	205	E722	±45°	
13	CARBON	205	E722	0°	

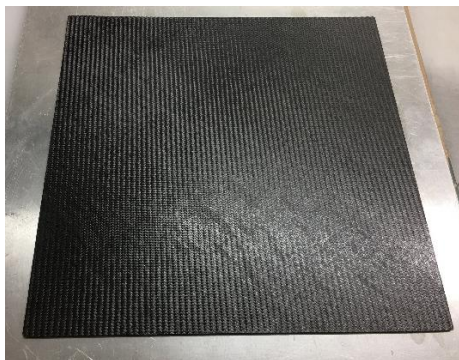
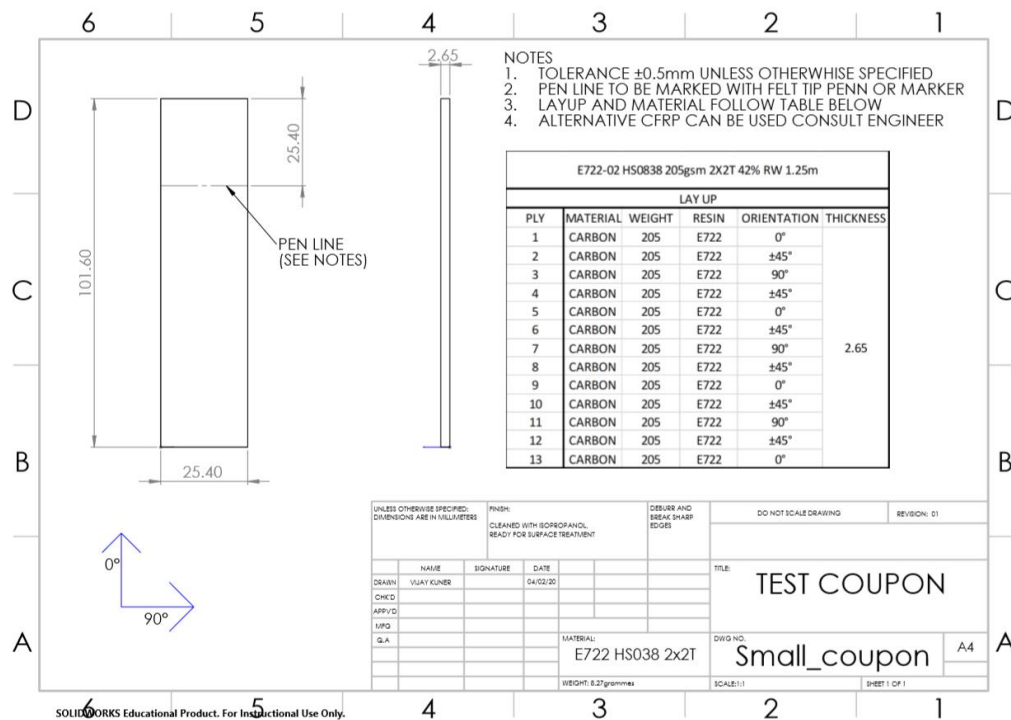


Figure 18 – Layup of Carbon Fibre on Steel Plate

3. **Bag and cure:** in autoclave for 60mins at 120°C and a pressure of 6BAR, as shown in datasheet. (TENCATE, 2013)
4. Once carbon plate was cured, it was allowed to cool down and then **cut to desired size**. If the coupons were to be cut to D5868 spec for bonding specimens, Drawing 1 was followed, for D5961 spec Figure 12 and 13 were used, with a hole drilled for the rivets in the locations shown by the D5961 locations.



Drawing 1 – D5868 Technical drawing for bonded coupons.



Figure 19 – D5868 for bond testing.



Figure 20 – D5961 for rivet testing.

The reason Figure 20 has a speckled pattern is for the DIC to be able to track its displacement around the hole.

6.2.2 Surface Treatment procedure

There were three different surface treatment procedures undertaken: shot blasting, vapour blasting and plasma treatment. Within the plasma treatment there are thirteen different configurations of exposure time and nozzle distance to the coupon.

1. **Shot Blasting and Vapour Blasting:** the only difference in this procedure is the use of either a shot blaster or vapour blaster machine. The steps taken were:
 - a. Degreasing and cleaning the component with isopropanol and a lint free cloth.
 - b. Masking regions that did not require bonding preparation with flash tape Figure 21. A sufficient gap was left around the borderline for adhesive fillet.



Figure 21 – Masked off area

- c. For shot blasted specimens: The unmasked part of the surface was abraded by means of a Grit Blast shot blasted to Ra 3-5, using a smooth action to ensure a uniform coverage.
- d. For vapour blasted specimens: the unmasked part of the surface was abraded by means of a Vapour Blast, using a smooth action to ensure a uniform coverage.



Figure 22 – Shot blasting machine on left, vapour blasting machine on right.

- e. Once blasted, any grit was cleaned away using water and IPA, then dabbed dry with a lint free cloth, ensuring that all cleaning agents had evaporated.
- f. Components were then stored in a sealed polythene bag until the time of bonding.

- 2. Plasma Treatment:** the coupons were treated with an atmospheric blow ion plasma treater at Enercon in Aylesbury. A multinozzle machine was used.
- a. The coupons were taped down on the conveyor line, which took the coupons under the plasma flame.
 - b. The speed of the conveyor belt was controlled by the knob indicated in the red circle in Figure 23. The speed was measured with the use of a tachometer, circled in green.

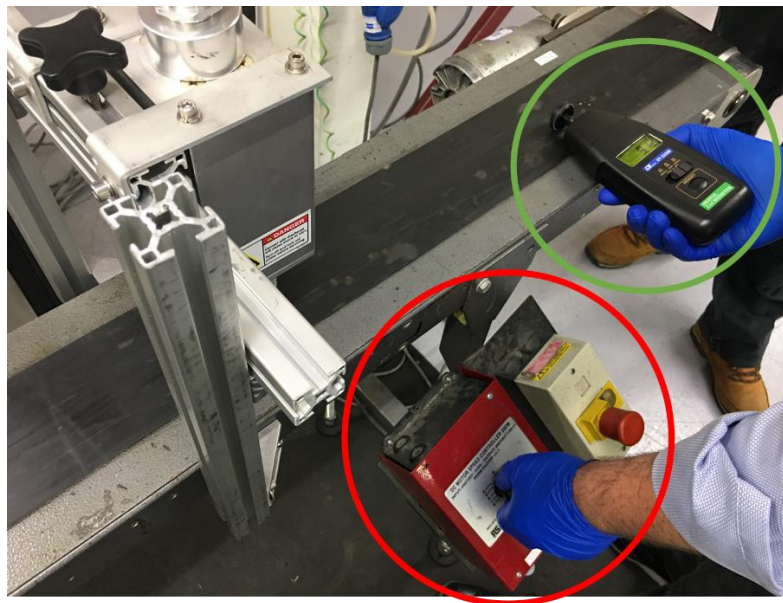


Figure 23 – Conveyor belt speed.

- c. The height of the nozzle, red circle Figure 24, to the coupon could be adjusted by loosening and tightening the aluminium extrusion frame accordingly and sliding the nozzle up and down as desired, blue arrow Figure 24.

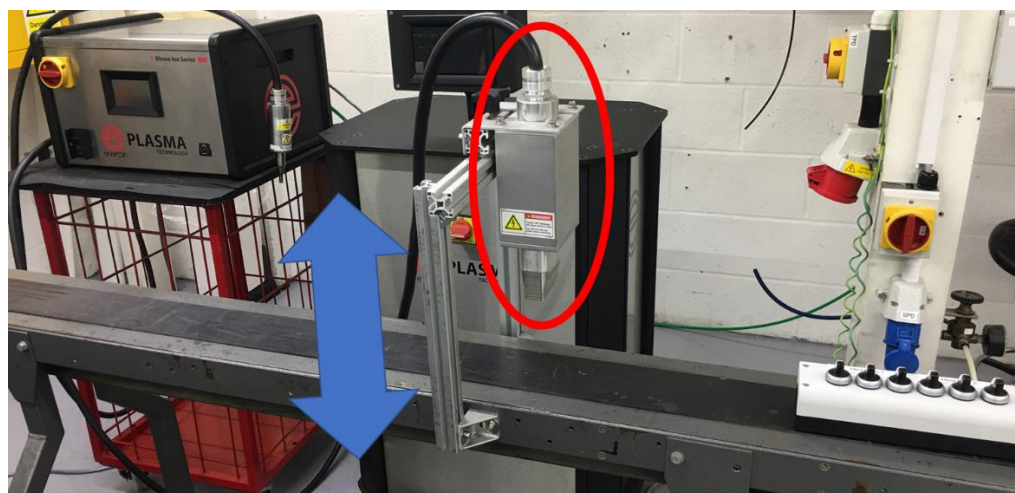


Figure 24 – Nozzle height adjustment

- d. Once the desired height and speed were found, the coupons could be plasma treated.



Figure 25 – Plasma treating coupons.

- e. Once they were all plasma treated, the plasma treated faces of the coupons were taped to each other and placed in separate bags for transportation to avoid contamination.

6.2.3 Roughness and surface energy measurements

The roughness was measured for the shot blasted and vapour blasted coupons, while the surface energy was measured for the plasma treated coupons.

1. **Roughness Measurement:** a measurement of the roughness was made on the shot or vapour blasted surface and also on the untreated surface next to it for comparison.

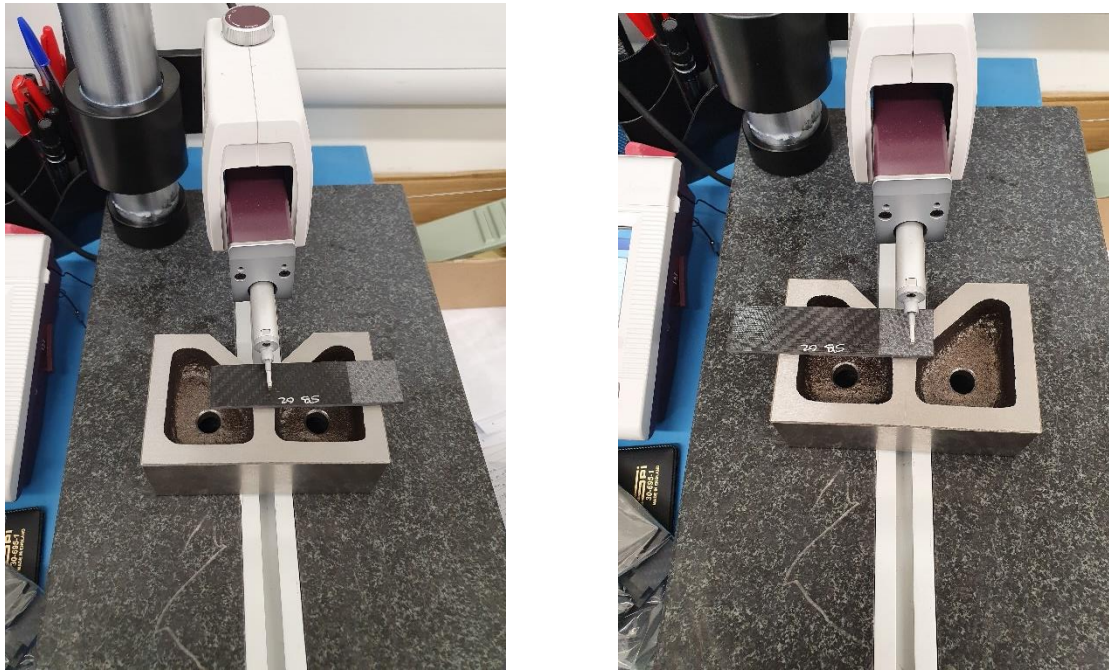


Figure 26 – On the left roughness measurement taken on untreated surface, on the right measurement on treated.

The higher the roughness measurement the better the adhesion should be theoretically. The downside is that shot blasting and vapour blasting carbon fibre for too long can seriously damage the fibres within the composite.

2. **Surface energy measurement:** the surface energy of each plasma treated coupon was measured using dyne pens, these kind of pens gives the uses an approximate measurement of the surface energy of each coupon.
- Start from the highest dyne pen available and work down till a good wetting is found. When a good wetting is found the dyne pen number is written down and that is the surface energy of that solid.
 - To avoid contamination of the bonding area with dyne pen liquid, the dyne pen was used on an area where the adhesive is not placed, the whole coupon was plasma treated for this purpose.



Figure 27 – Dyne pen liquid on the left, dyne pens on the right.

3. Contact angle measurement and Surface energy measurement: a more accurate way of calculating the surface energy is by the way of contact angles.

- a. A drop of water was placed on the plasma treated surface and then a photo was taken with a macro lens camera.
- b. This photo was then inputted into a photo editing software called **ImageJ**. Within this software there is a plugin called **LBADSA**, this is a method based on the Young Laplace equation for measuring contact angles and surface tensions. It takes the drop contour from a photo taken and measures it by using the pixels within the photo as units of measure. From these photos the contact angle is measured. In Figure 28, the contact angle is within the red box, in this case 62.235° . (Aurelien F. Stalder, 2010)

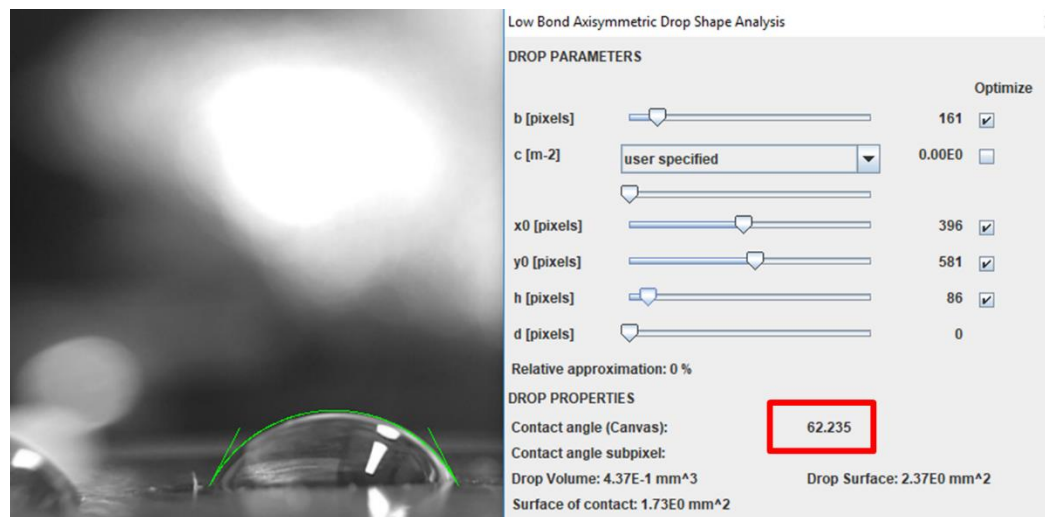


Figure 28 – LBADSA contact angle measurement of water droplet.

- c. Unfortunately, due to unforeseen circumstances the use of a microscope was necessary for getting an accurate read for an n-octane drop. This was because the n-octane has only dispersive values and a much lower surface tension than water; the droplets spread out too much and it was not possible to get an accurate picture with a standard camera. For the sake of argument, let's assume that it was possible to get the measurement. Once the photo was taken and taken through the same process as the previous point, both contact angles would be used to calculate the surface energy by using the Fowkes theorem as explained in section 5.5.5.
- d. As this measurement could not be made, the dyne pen measurements were used to compare results. The point of this procedure being made was to attempt to validate the dyne pen results, but this could not be done.

6.2.4 Riveted, bonded and hybrid coupons

1. **Riveted Coupons:** Single hole coupons and double hole coupons were riveted together using a rivet gun with 5mm rivets.



Figure 29 – The left image has the rivet gun; the right image is the rivet used.

The single riveted coupons looked like Figure 30 and double riveted coupons like Figure 31.



Figure 30 – single riveted coupon



Figure 31 – double riveted coupon

2. **Bonded Coupons:** the use of a jig was necessary to control bond thickness.

a. Preparing bonding jig for coupon bonding:

- i. Wipe jig clean with isopropanol.
- ii. Wipe entire jig with release agent.
- iii. Leave jig in release room, until it is needed



Figure 32 – Bonding jig

b. Bonding coupons together:

- i. DP490 is applied to coupon on abraded area, Figure 33.
- ii. Place 0.8mm rod across the bondline aided by the jig, Figure 33.
- iii. The adhesive bondline thickness is controlled by the jig and rod
- iv. Give each bonded coupon a serial number provided as a tag.

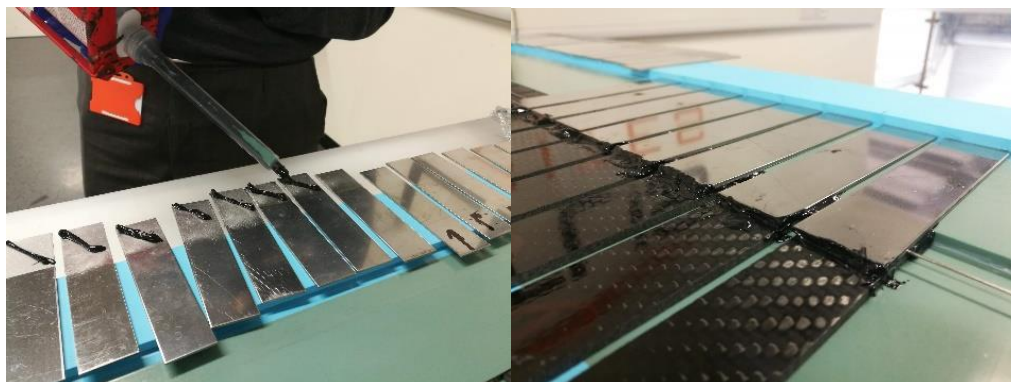


Figure 33 – DP490 applied on coupon on left; rod placed on the right.

- v. Place metallic plates over the jig and two weights on top to put some pressure on bond area, Figure 34.



Figure 34 – Metallic plate and weights on coupon

- vi. Cure in oven for 1 hour at 80°C, Figure 35.



Figure 35 – Cure in oven.

- vii. Once cooled down, remove the coupons from jig.
- viii. Store in polythene bag

3. **Hybrid Coupons:** These coupons have been previously shot blasted and then had DP490 placed on the treated area, as seen in Figures 36 and 37. After the glue has been placed on the treated areas a rivet is used to join the two coupons together, the pressure placed by the rivet dictates the bond thickness which the coupon assembly will have.

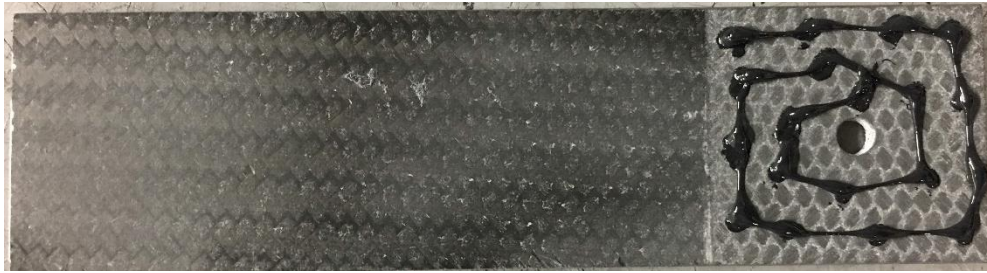


Figure 36 – Single hole hybrid coupon

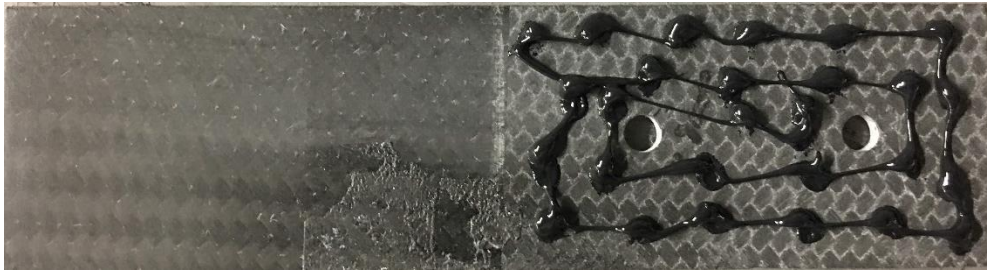


Figure 37 – Double hole hybrid coupon

Once riveted together they are placed in the oven for 1 hour at 80°C.

6.3 Tensile Test procedure

Once all coupons are ready and assembled as needed, they are ready to be tensile tested.

1. Coupons are placed in the grips, making sure they are parallel to the tensile load. These grips are then tightened to hold the coupons in place, it is not necessary to torque the bolts to a certain value.



Figure 38 – Grips holding coupon in place.

2. The grips are then placed into the jaws of the tensile test rig, Figure 39.



Figure 39 – Grips placed onto rig.

3. Tensile testing procedure within the elastic region:

- a. Set two trips up
- b. Load max upper limit 3kN
- c. Disp max upper limit -40mm
- d. Make sure it is updated, pink screen means it is not.
- e. Open Data logger make sure the setup is all correct.
- f. Turn pressure on, get all residual slack out by applying and releasing load within the elastic region of the component.
- g. On the Manual Control, set at 0.1kN/sec.
- h. Once test is done Stop run, spool and close.
- i. Record all DATA

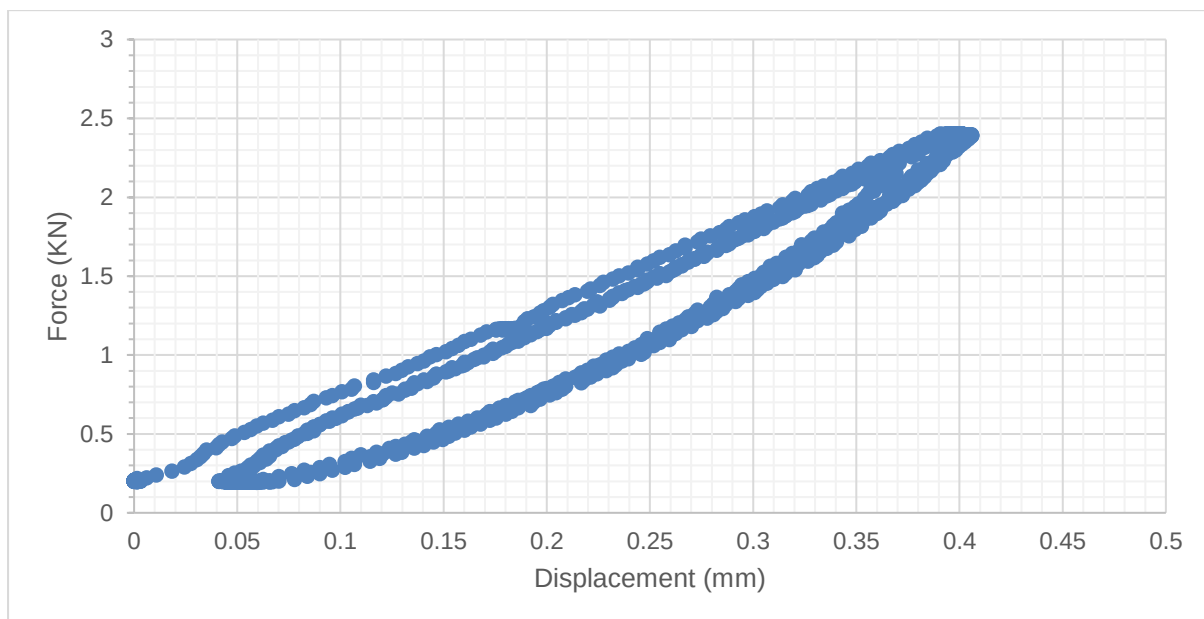
4. Tensile testing until failure:

- a. Set two trips up
- b. Load max upper limit Failure kN
- c. Disp max upper limit -40mm
- d. Make sure it is updated, pink screen means it is not.
- e. Open Data logger make sure the setup is all correct.
- f. Turn pressure on, get all residual slack out, by applying and releasing load within the elastic region of the component.
- g. On the Manual Control, set at 0.1kN/sec.
- h. Once test is done, Stop run, spool and close.
- i. Record all DATA

Once all data is recorded analysis of the data can be done.

7 Results

During testing the slack within the tensile testing machine was taken away by loading and unloading the joint specimens, this forms a hysteresis. “A hysteresis forms when a specimen is successively subjected to the application of a load or stress less than that causing rupture and to the removal of the load or stress according to a predetermined procedure” (J.W., 2011). This hysteresis happened with every joint specimen tested.



Graph 5 – Hysteresis created by loading and unloading joint specimen.

The riveted and hybrid are named as in table 5. The plasma treated coupons are named as in table 6. The shot Blasted and Vapour Blasted are named as in table 7.

Table 5 – Riveted and hybrid naming convention.

19	11	28	-	01 to 35
Year (2019)	Month	Day	-	Iteration number

Table 6 – Plasma Treated naming convention.

6 to 27.5	12 to 17	01 to 04
Line Speed (m/min)	Distance nozzle to coupon (mm)	Iteration number

Table 7 – Shot Blasted and Vapour Blasted naming convention.

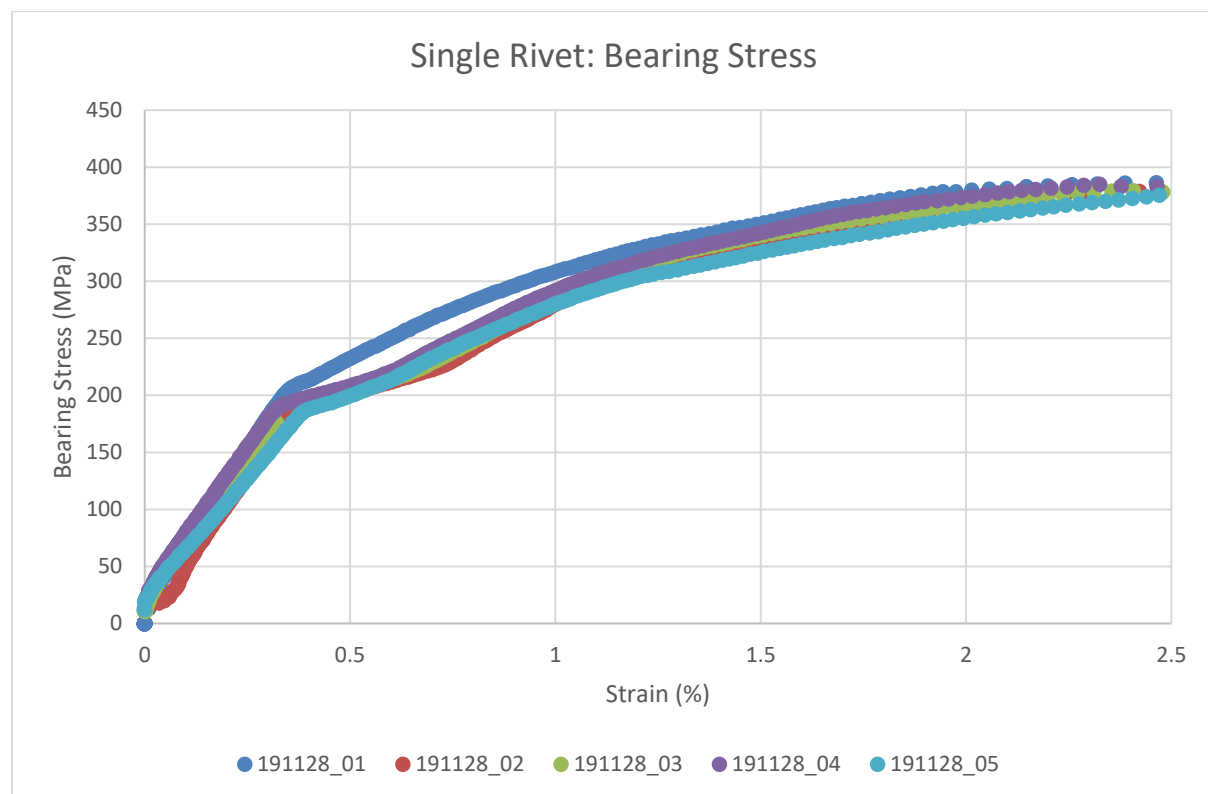
SB or VB	10 to 80
Shot Blasted or Vapour Blasted	Iteration number

7.1 Riveted

The bearing stress was calculated for each individual joint. The following equation for bearing stress was used:

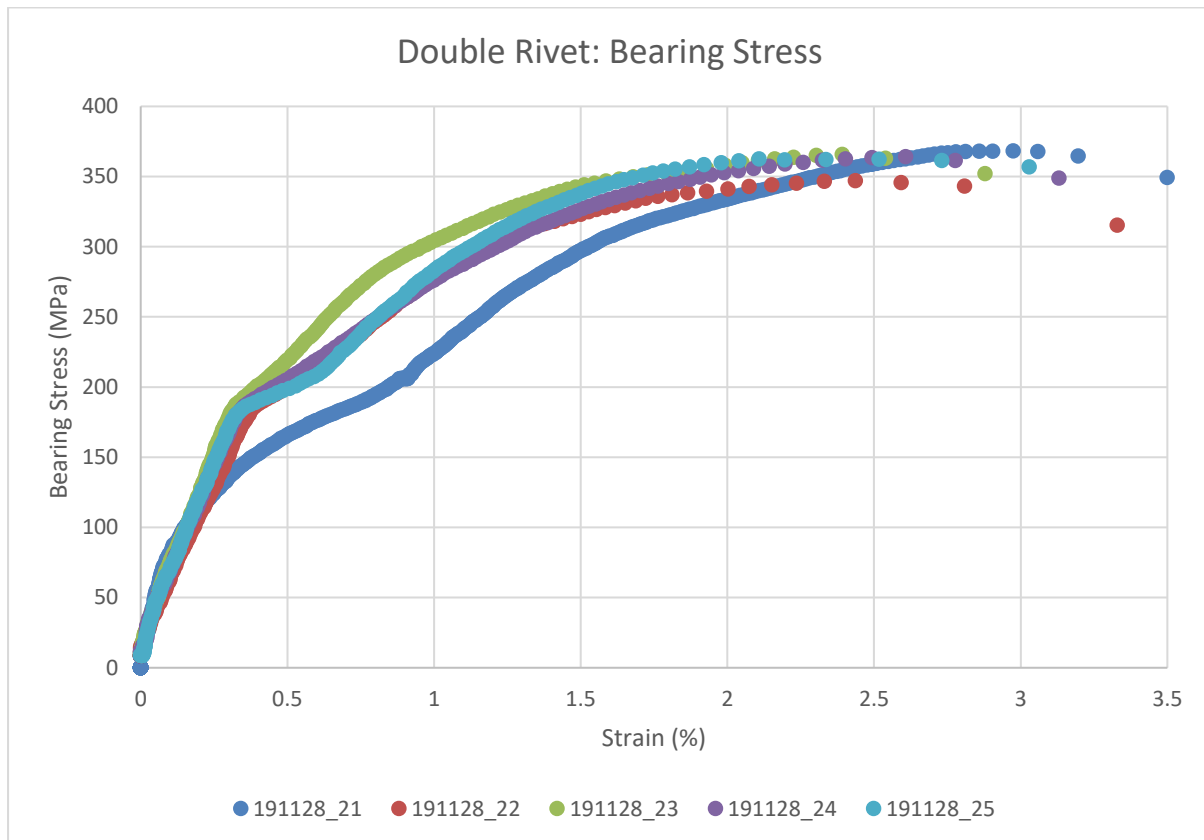
$$\text{Bearing Stress} = \frac{\text{Load}}{\text{Thickness of coupon} \times \text{Hole Diameter}} \quad \text{Equation 7 – Bearing Stress}$$

The more rivets added to a joint specimen, the more bearing area there will be, therefore the stresses will be lower. This phenomenon can be seen by looking at Graph 6 and 7. The max bearing stress in the single riveted joint is 386.5MPa and in the double riveted joint is 365.66 MPa. These two bearing stresses are similar because they were both taken at their max loads of 5.79kN and 10.97kN respectively. If the bearing stress from the double riveted joint is taken at the same failure load as the single riveted joint there is a bearing stress of 192.56MPa, thanks to that extra rivet the bearing stress can be shared across two rivets and therefore take a much higher load.



Graph 6 – Single Rivet: Bearing Stress

In Graph 6 there is one specimen, 191128_01, which takes a different path to the conventional one. This is because the material on that specific specimen is slightly thicker, 0.3mm than the average. This slight increase in thickness helps the rivet take more stress than the average, thanks to there being a larger surface area, on which the load is acting on.



Graph 7 – Double Rivet: Bearing Stress

In Graph 7 there is a big change in path with specimen 191128_21, this is because there has been a big tear of the material. The carbon fibre around one of the rivets failed before the rivet, as seen in Figure 40, therefore the path for specimen 191128_21 is different to the conventional. Measurement of the thickness of each coupon shows that there is a difference of 0.5mm between the two joint specimens in Figure 40. This difference in thickness has affected specimen 191128_21. Interestingly it managed to achieve the highest bearing stress from the lot, this is because, while the material was tearing, the surface area on which the rivet was resting increased while the tear was happening.



Figure 40 – On the left specimen 191128_21, on the right specimen 191128_24

7.2 Hybrid

The bearing stress and the shear stress were calculated for each hybrid joint. The Adhesive shear stress equation and the Normal stress equations used are the following:

$$\text{Adhesive Shear Stress} = \frac{\text{Load}}{\text{Bonded Area}} \quad \text{Equation 8 – Adhesive Shear Stress}$$

$$\text{Normal Stress} = \frac{\text{Load}}{\text{Width} \times \text{Thickness}} \quad \text{Equation 9 – Normal Stress}$$

The bearing stress graphs can be found in Appendix C. The bearing stresses acting on the joint hinder the component, as it produces stress concentrations in that area. All the hybrid specimens had structural fails due to these holes, as seen in Figure 42. A structural fail is when the carbon fibre fails near the adhesive bond, as seen in Figure 41 and Figure 42. (EcoEnclose, 2019)

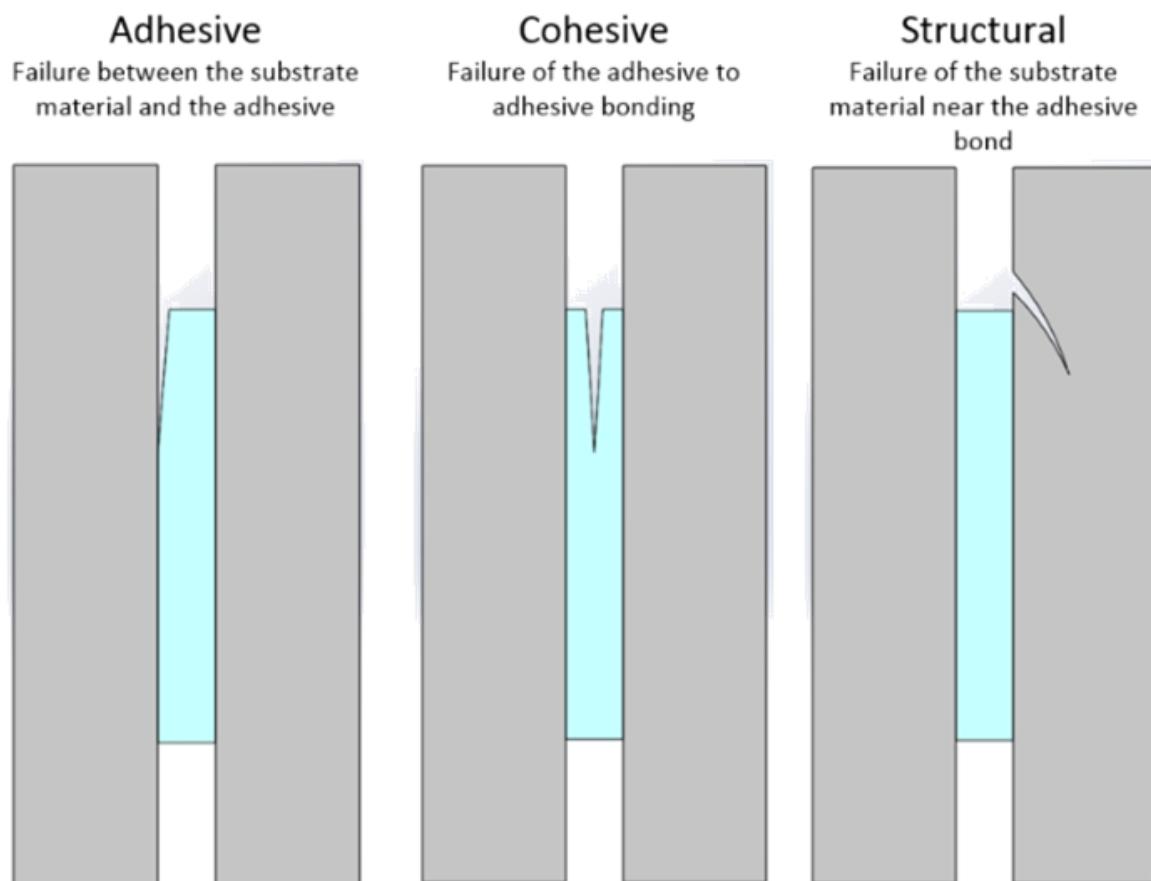
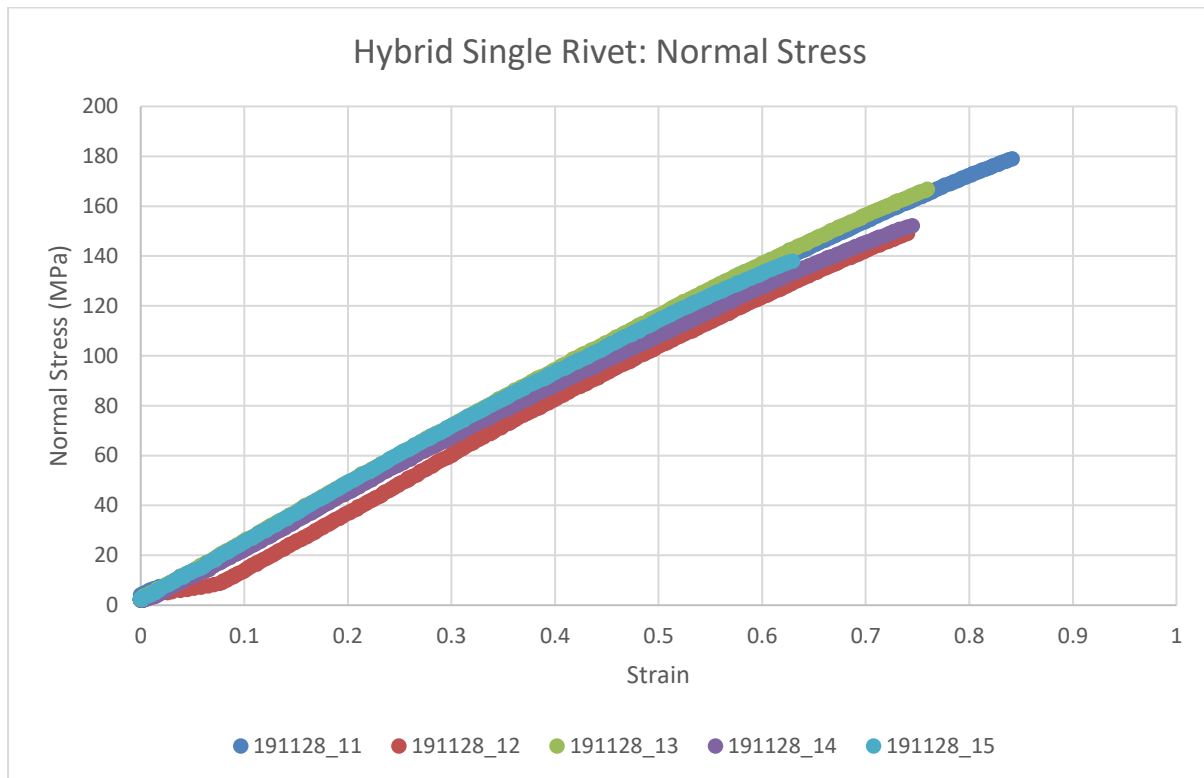


Figure 41 – Adhesive, Cohesive and Structural failure modes. (EcoEnclose, 2019)

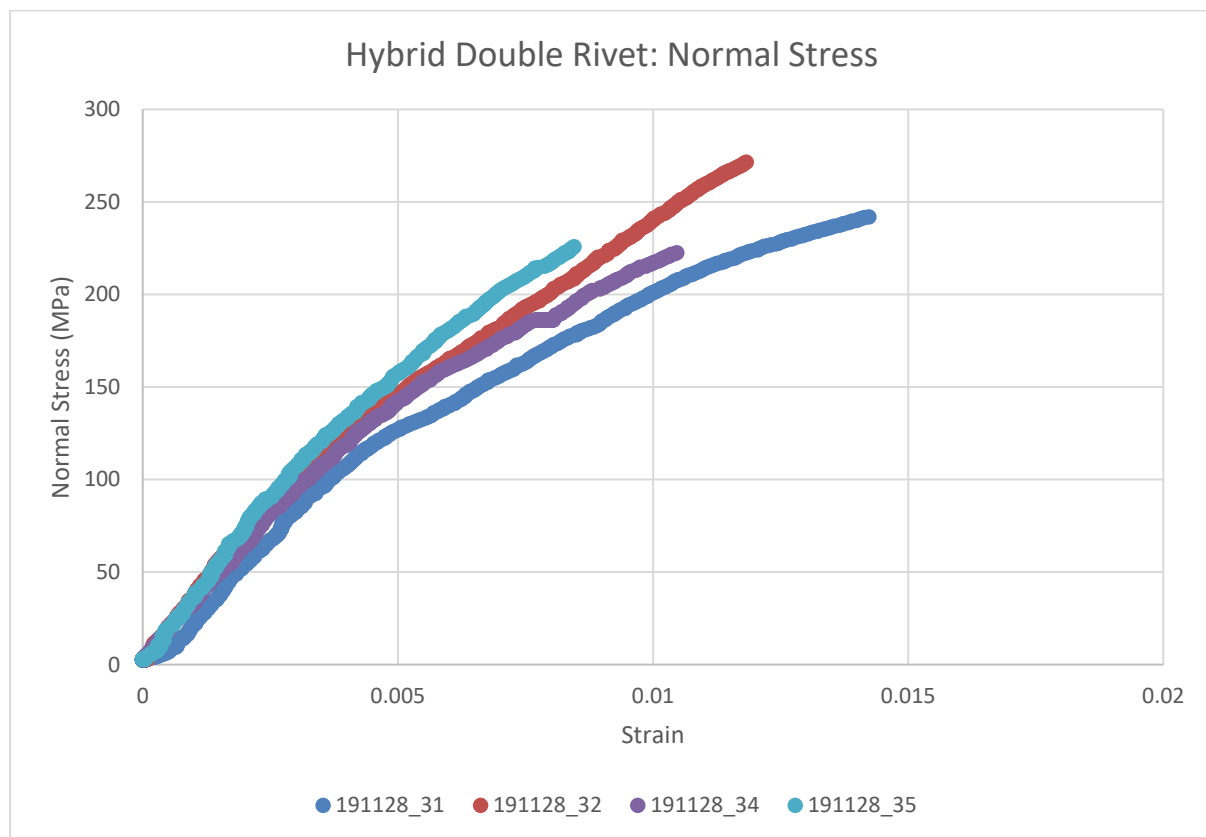


Graph 8 – Hybrid Single Rivet : Normal Stress.

The specimens in Graph 8 all had a structural failure, the first ply of the coupon failed and gave way. This happened as the stresses acting on the carbon fibre are higher than what the material datasheet implies. The in-plane shear stress of the carbon fibre was 112MPa (TENCATE, 2013), the max stress applied on to the material is 178.8MPa. The material failed before the adhesive; this is because the max Adhesive Shear Stress was 15.137 MPa, while the DP490 material datasheet said that the max shear stress for the glue at 23°C is 30.2MPa (3M, 1996). The max load applied on the coupon was 19.32KN



Figure 42 – First Ply failure, part 191128_14



Graph 9 – Hybrid Double Rivet: Normal Stress.

Graph 9, the adhesive makes the bearing bypass interaction between the two rivets become unpredictable. Due to this, specimens 191128_32, 191128_34 and 191128_35 follow the same path, they break at different points due to the material properties. On the other hand, component 191128_35 had a complete structural failure exactly along the line where the hole is, as seen in Figure 42.

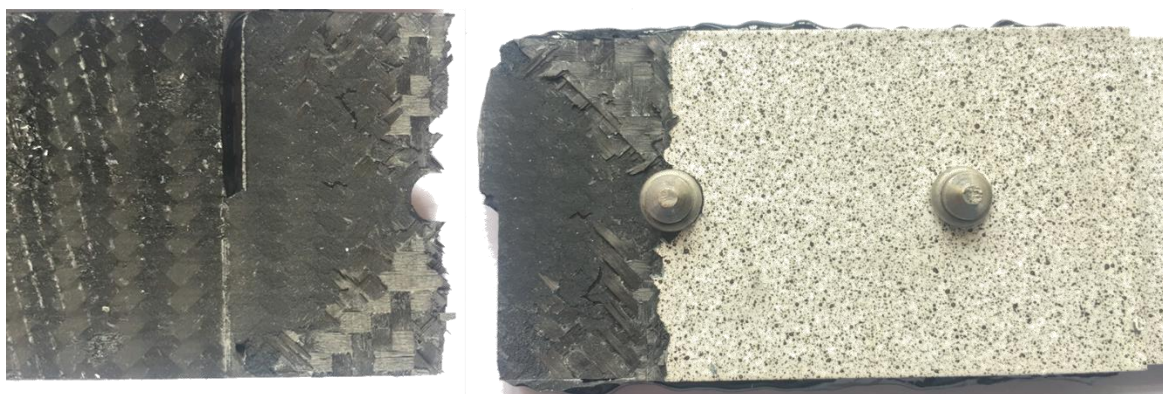
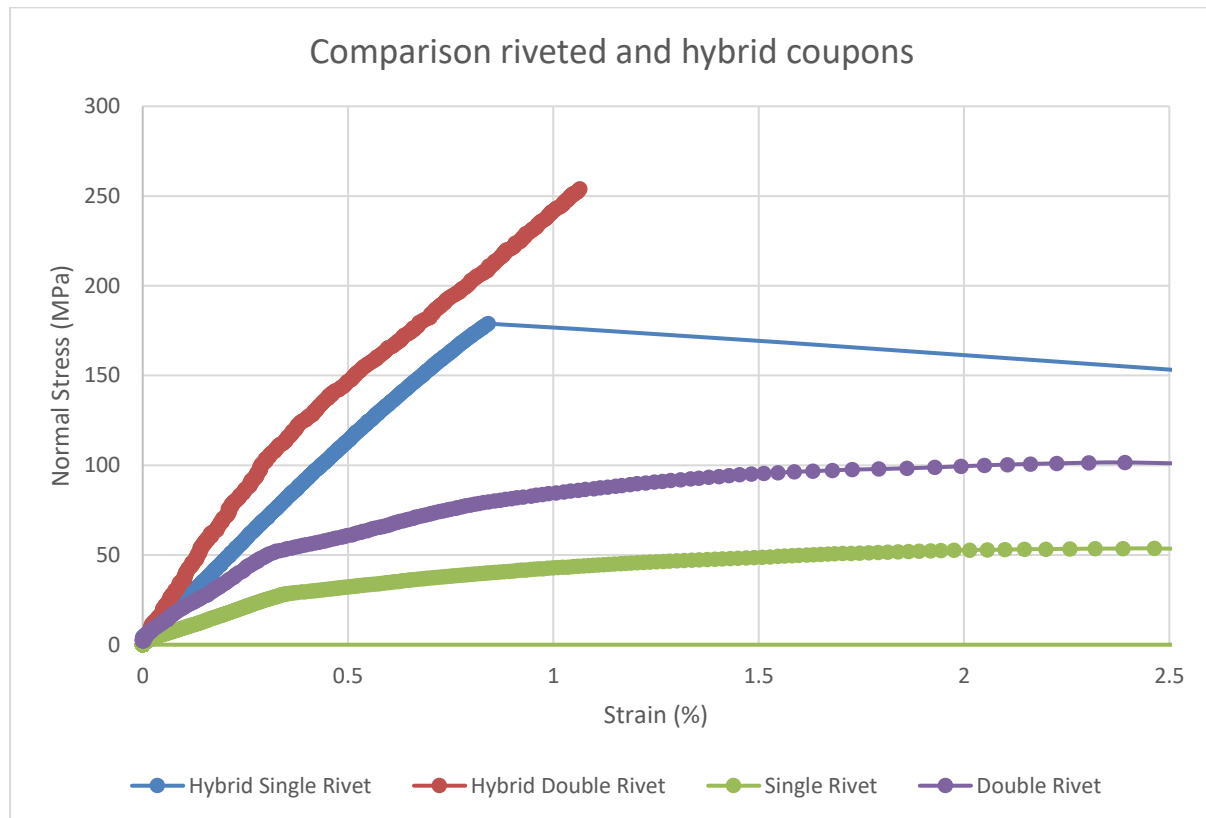


Figure 43 – Structural failure of the carbon fibre, part 191128_31

7.3 Comparison of riveted joints and hybrid joints.

A comparison of the strengths of riveted and hybrid joints can be seen in Graph 10.



Graph 10 – Comparison riveted and hybrid coupons

It is apparent from graph 10 that extra rivets give the best results, although they are hindering the bond of both coupons with the presence of stress concentrations where the holes are. Due to this, the holes and rivets have been removed all together in the next section of this paper. The removal of these rivets and holes should in theory remove these stress concentrations and improve the joining of both coupons.

7.4 Plasma treated joints

The coupons were plasma treated at Enercon. They were dyne tested, from which the Surface Free Energy of each coupon was found, as seen in Table 8.

Table 8 – Plasma configurations with surface free energy

Exposure Time per mm	Line Speed (m/min)	Distance (mm)	Surface Free Energy (mN/m)	Number of coupons
0.25	6	12	71	10
0.13	12	12	69	10
0.08	18	12	71	10
0.06	24	12	67	10
0.06	27.5	12	69	10
0.25	6	14	63	10
0.13	12	14	52	10
0.08	18	14	48	10
0.06	24	14	48	10
0.25	6	17	52	10
0.13	12	17	48	10
0.08	18	17	46	10
0.06	24	17	46	10

Three different nozzles to coupon distances and five different line speeds were used. Looking at table 8, the exposure time of each mm of carbon fibre to plasma is very low due to the minimum and maximum line speeds of the conveyor belt used - between 6 and 27.5m/min.

All the coupons at the 12mm distance have very similar values one to each other. The line speed does not affect the energy levels as much as the distance at this level. On the other hand, at bigger distances such as 14mm and 17mm the line speed does affect the coupons in a larger manner. Highest energy level at a 14mm distance is found at its lowest line speed of 6m/min. Furthermore, the lowest energy level at a 14mm distance is found at its two highest line speeds of 18m/min and 24m/min. The same happens for the coupons at a 17mm distance from the nozzles.

To validate these surface energy levels additional wettability testing was planned, but the use of a microscope was necessary and due to the pandemic, it could not be done.

7.4.1 Tensile Testing Plasma treated coupons

All plasma treated coupons had adhesive failures, where they failed between the glue and the carbon fibre as seen in Figure 44. When failure happened the carbon was bare on one coupon with no signs of broken fibres or matrix degradation, while on the other coupon the adhesive was still stuck on that surface; this is a clear sign of adhesion failure. This happens when the treatment used does not create the correct conditions for a good bond.

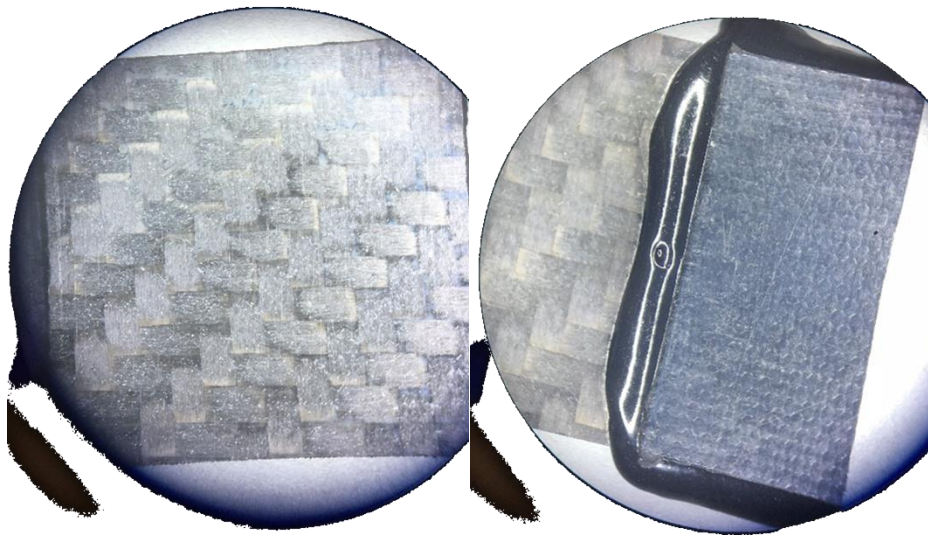
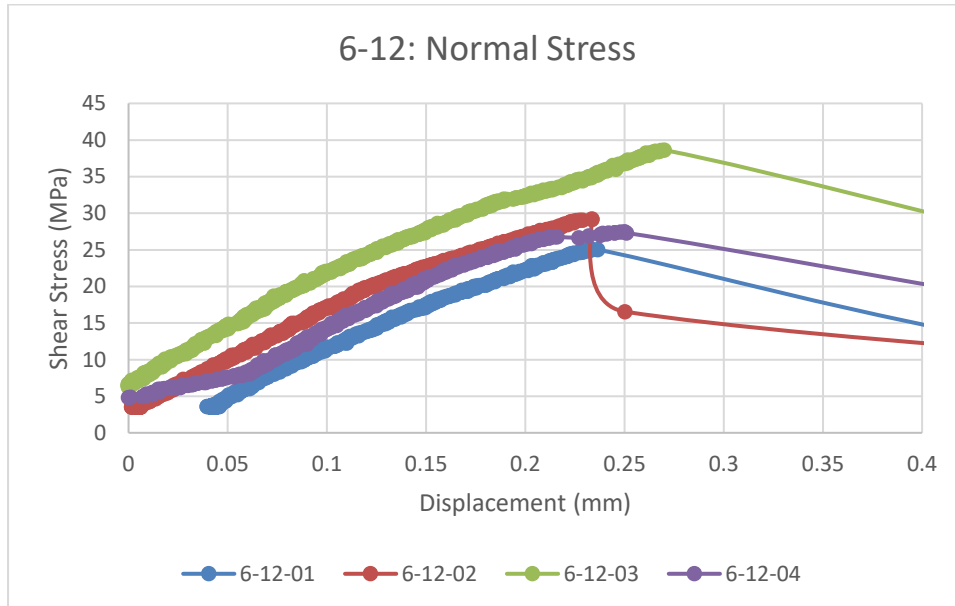


Figure 44 – Adhesive Failure of plasma treated coupon, on the left bare carbon after test, on the right adhesive.

For the comparison between plasma treated components the normal stress will be used. Due to the difference in size of coupons for the riveted specimens and the bonded specimens, the adhesive shear stress will be compared to each other to put them all on the same playing field.

7.4.2 Problem solving

In Appendix C all the individual Normal Stress and Adhesive Stress graphs can be seen.

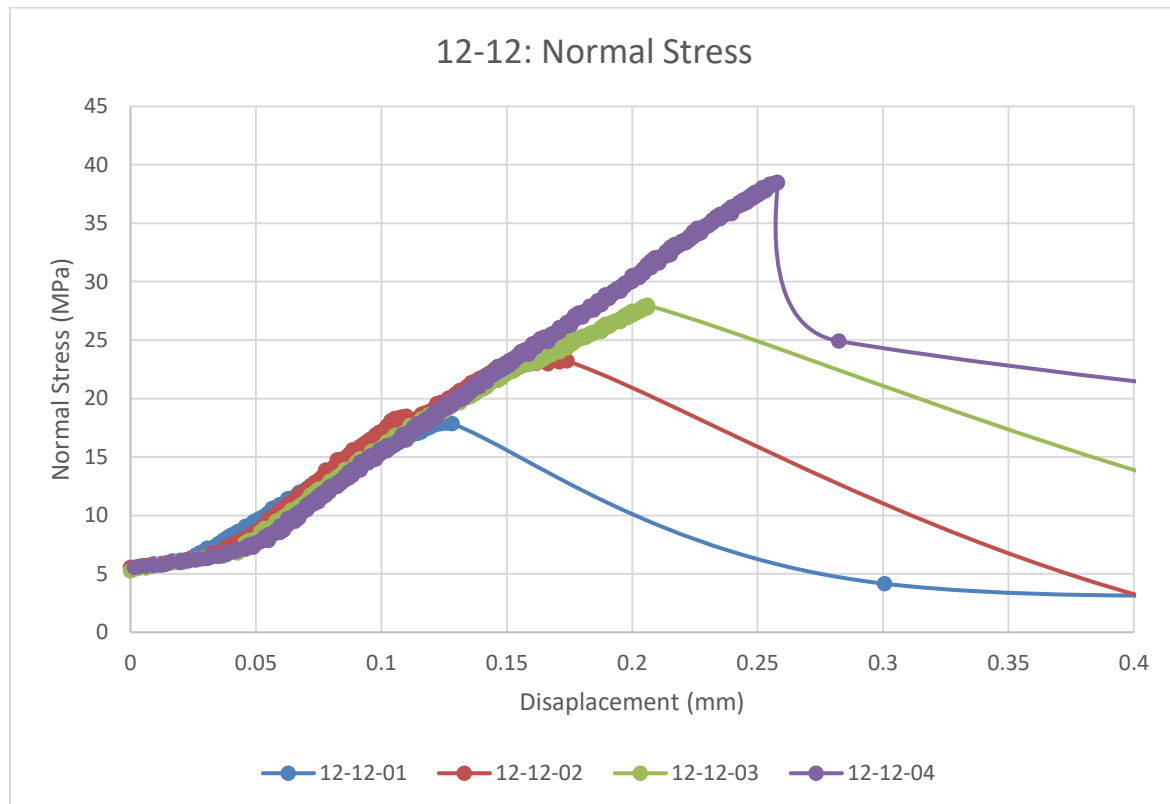


Graph 11 – Normal Stress, parts 6-12

All the normal stress graphs for the plasma treated coupons look like Graph 11, the different iterations within each plasma treatment configuration failed at different points and did not follow similar paths to each other. One assumption that can be made is that they are not as close to each other due to them failing at very low loads in comparison to previous testing. Furthermore, measurements of the thickness of each coupon and bond thickness was done after testing. This was possible because the failure mode was an adhesive failure, therefore the glue is still on the coupon. Table 9 shows the bond thickness of the coupons used for Graph 11, The bond thickness is pretty much the same for the 4 iterations. This tells the user that the problem is the plasma treatment, a possibility is that when the plasma hit the coupons on the edge of the line it created a vortex in that step from the conveyor belt to the coupon. This might have made the plasma not spread evenly across the coupon and this would have made the bond weak as full adhesion would not have been possible.

Table 9 – Bond thickness of part 6-12

Name (Pairs)	CFRP Thickness	Overall Thickness	Adhesive
6_12_01	3.23	4.37	1.14
6_12_02	3.4	4.39	0.99
6_12_03	3.38	4.39	1.01
6_12_04	3.36	4.32	0.96



Graph 12 – Normal Stress, parts 12-12

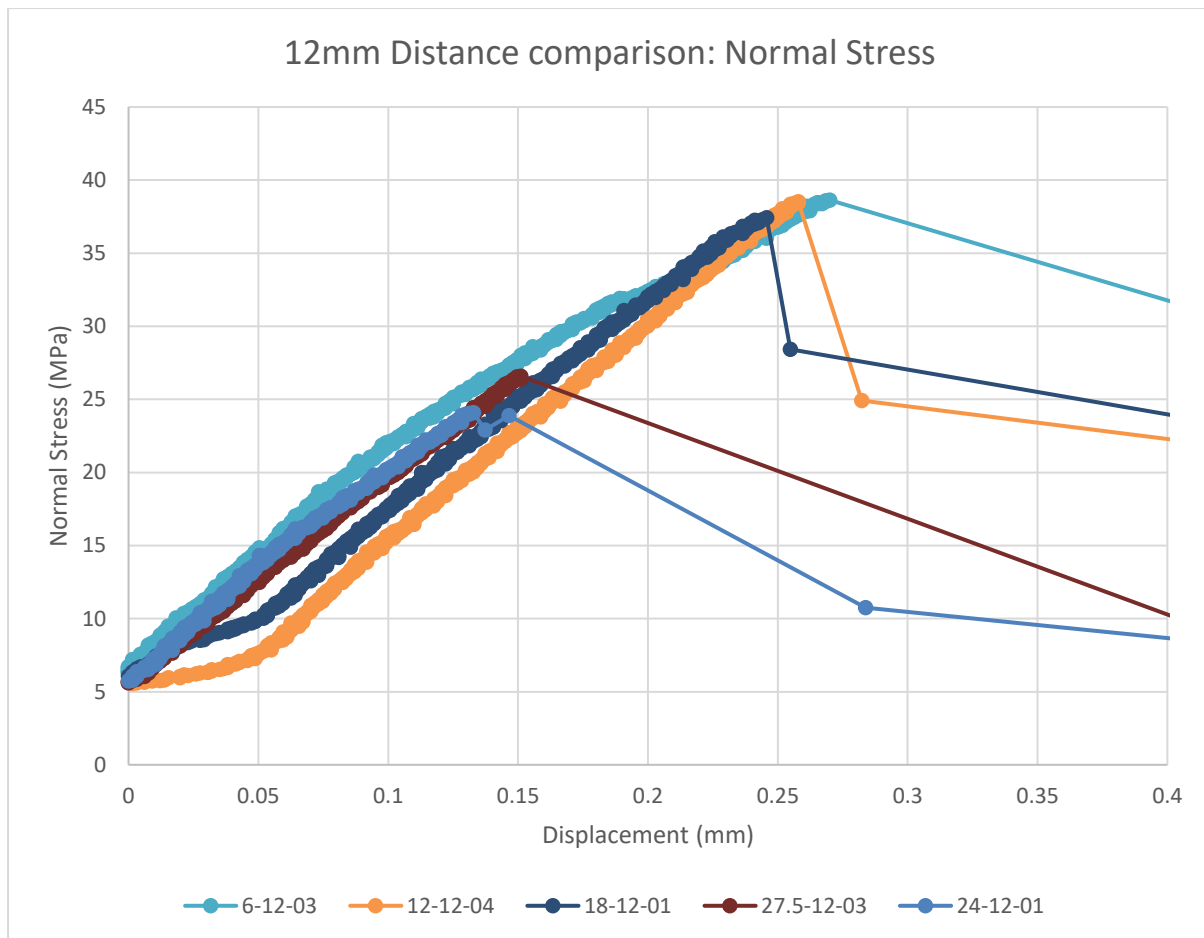
The specimens in graph 12 are following the same path to each other but they are failing at very different loads. Looking at table 10 it can be seen that the adhesive thicknesses change dramatically one to each other. Due to this discrepancy in bond line thickness the coupons have been failing at different loads, the reasoning to explain this discrepancy is that the carbon fibre thickness varies from one coupon to the other, as seen in table 10. This is possibly due to the incorrect layup of the carbon initially.

Table 10 – Bond Thickness of part 12-12

Name (Pairs)	CFRP	Thickness	Adhesive
12_12_01	3.68	4.33	0.65
12_12_02	3.3	4.19	0.89
12_12_03	3.5	4.06	0.56
12_12_04	3.66	4.37	0.71

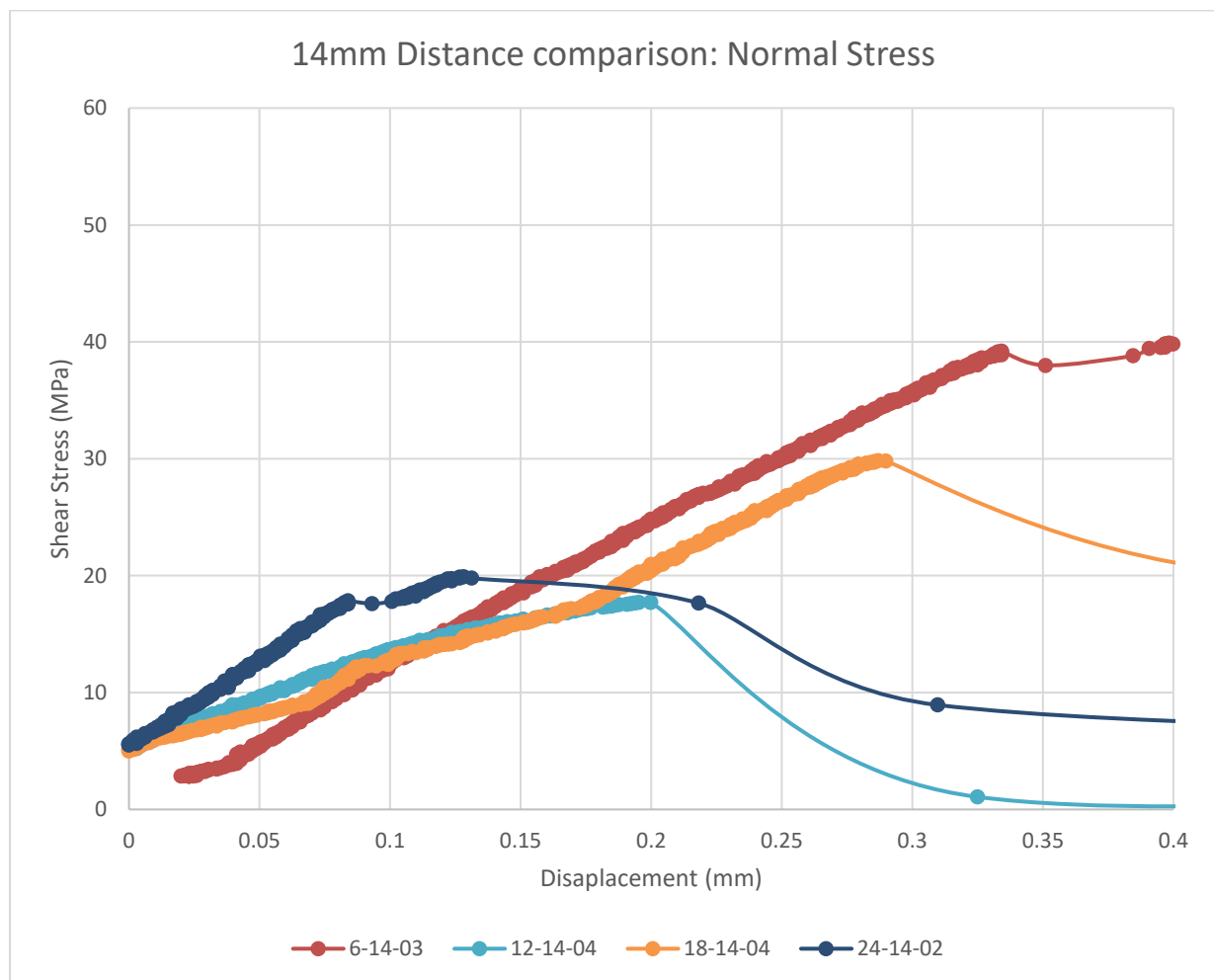
All the iterations within each plasma configuration have one of the problems explained above. To achieve some sort of comparison between plasma treated coupons, only the best-case scenario coupons have been taken, assuming that the procedure had been done correctly.

7.4.3 Comparison of plasma treated coupons



Graph 13 – 12mm Distance comparison

Graph 13 shows the max iteration within each 12mm distance configuration. The strongest component is number 6-12-03. This makes sense as it has the highest surface energy of the five with a level of 71 mN/m. This specimen reached a max stress of 38.633MPa nowhere near the material breaking point or the adhesive breaking point, which is why it experiences an adhesive failure. On the other hand, the weakest component is number 24-12-01. Out of the five it has the weakest surface energy level of 67mN/m, and due to this it failed at a load of 2.25KN, while the strongest component failed at a load of 3.55KN

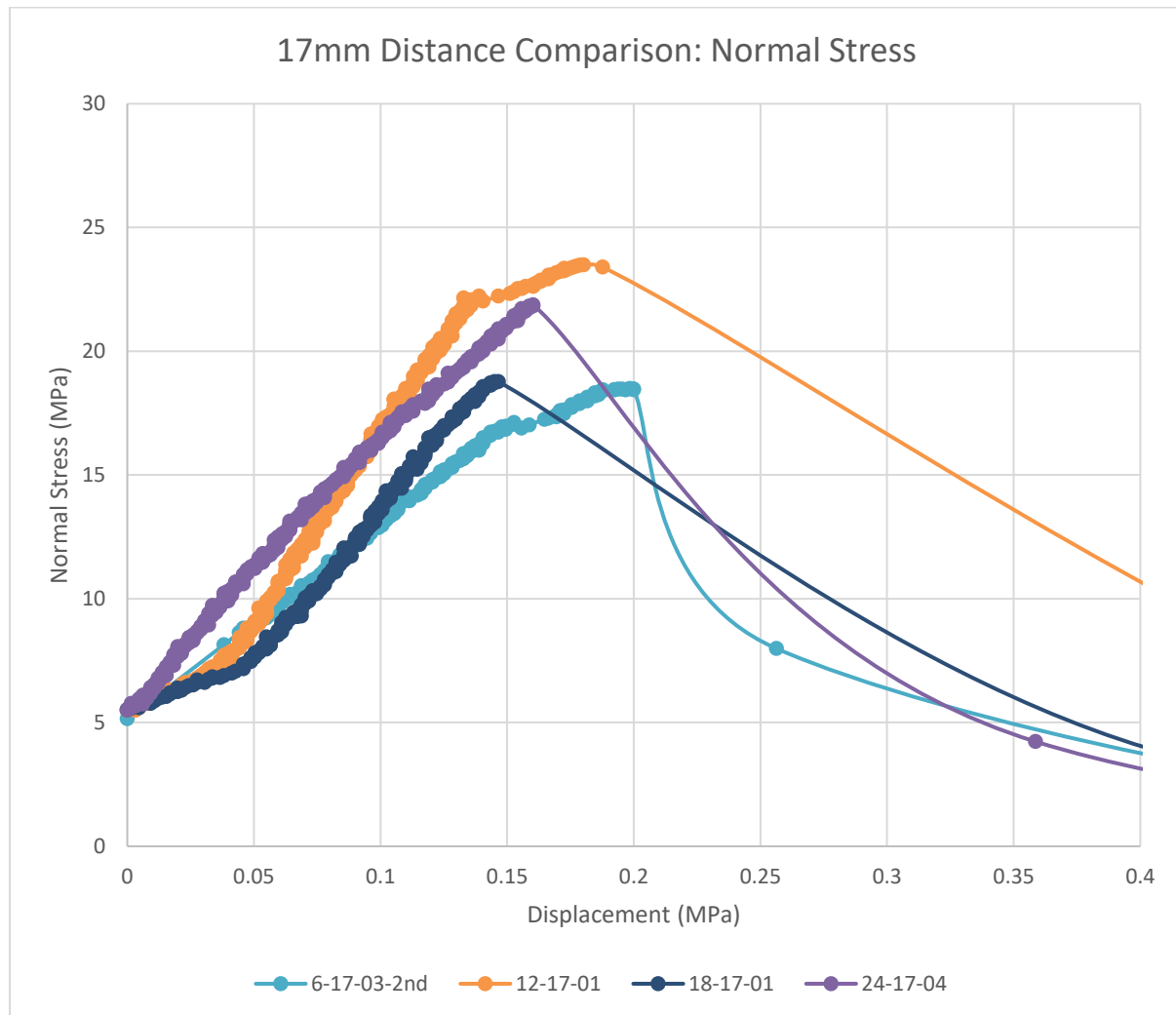


Graph 14 – 14mm distance comparison

There is great discrepancy between each component; specimen 6-14-03 fails at the highest load of 4.248kN and highest normal stress of 46.2MPa. Due to it having the lowest line speed of 6m/min, it has the highest surface energy level of 63mN/m. The lowest load goes to part 12-14-04 with a load of 1.63kN and the lowest normal stress of 17.74MPa. It doesn't have the lowest surface energy of the three, the remaining two have the lowest surface energy of 48mN/m, while it has 52mN/m but it has the highest bond thickness - a bond thickness of under 1mm is ideally the best.

Table 11 – Bond Thickness of specimens in graph 14

Name (Pairs)	CFRP	Thickness	Adhesive
6_14_03	3.43	4.38	0.95
12_14_04	3.33	4.34	1.01
18_14_04	3.65	4.12	0.47
24_14_02	3.63	4.57	0.94



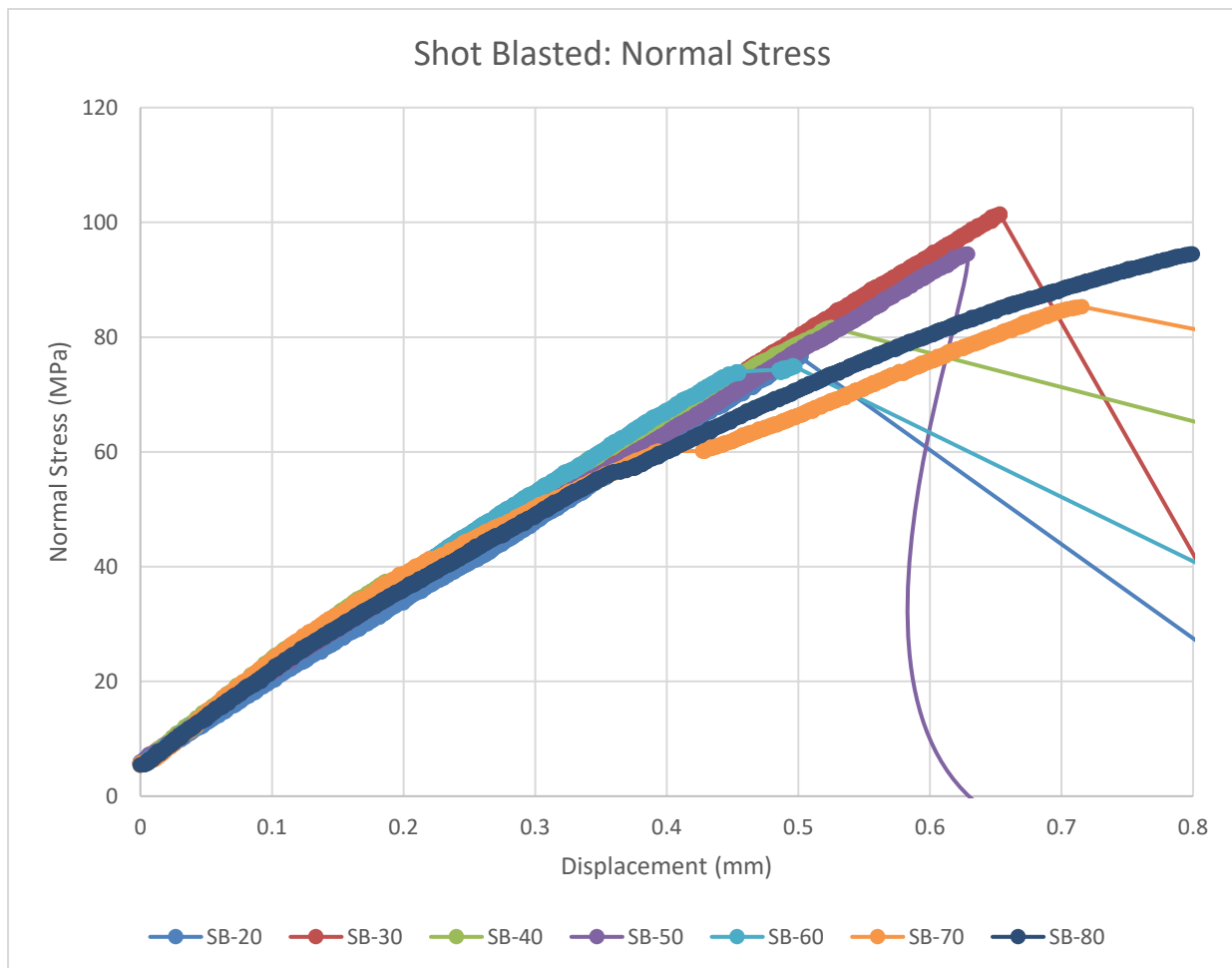
Graph 15 – 17mm Distance

There are slight differences between each component in graph 15. Components 12-17-01, 24-17-04 and 18-17-01 being the closest to 0.8mm bond (ASTM, 2014) have the highest loads of 2.16kN and 2.01 kN respectively. 6-17-03 has the highest surface energy of the four with a value of 52mN/m. This helped it take more load even if it had an adhesive thickness thicker than the previous two components.

Table 12 – Bond Thickness of specimens in Graph 15

Name (Pairs)	CFRP	Thickness	Adhesive
6_17_03	3.37	4.35	0.98
12_17_01	3.81	4.58	0.77
18_17_01	3.67	4.35	0.68
24_17_04	3.55	4.22	0.67

7.5 Shot Blasted specimens.



Graph 16 – Shot Blasted: Normal Stress

The strongest specimen in Graph 16 is SB-80, which reached a load of 9.91kN and a normal stress of 107.88MPa. Roughness measurements were taken of each coupon these measurements can be seen in table 13. The roughness measurement of SB-80 correlated with what it should be achieving. It has the highest roughness and therefore achieves the biggest load. This is not true for other components such as SB-50, which has the lowest roughness measurement and is beating other components with higher roughness measurements. This is assumed to be the difference in material and bond thickness, due to the layup of the component.

Table 13 – Roughness of Shot Blasted Coupons

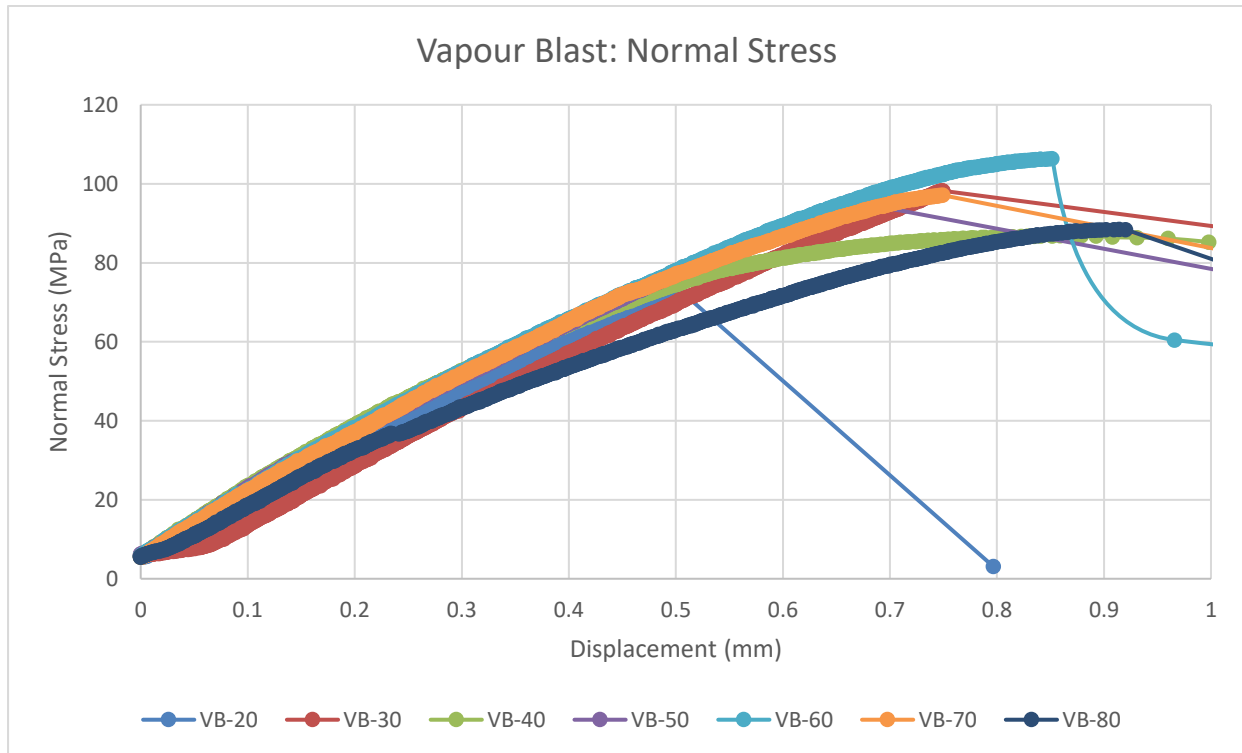
	Roughness Virgin Material	Roughness Treated Area
SB 20	4.359	0.6
	4.365	0.6
SB 30	4.603	0.702
	4.01	0.618
SB 40	3.84	0.712
	3.3	0.726
SB 50	4.928	0.429
	3.831	0.47
SB 60	3.099	0.546
	4.934	0.546
SB 70	2.621	0.492
	3.634	0.569
SB 80	4.442	0.723
	4.516	0.721

Shot blasted coupons all had structural failure. The carbon fibre gave way on the first ply of each coupon, as seen in Figure 45. The shot blasting degraded the surface of the coupon a lot more harshly than plasma treatment, therefore the first ply of the carbon fibre failed.



Figure 45 – Structural

7.6 Vapour Blasted specimens



Graph 17 – Vapour Blast: Normal Stress

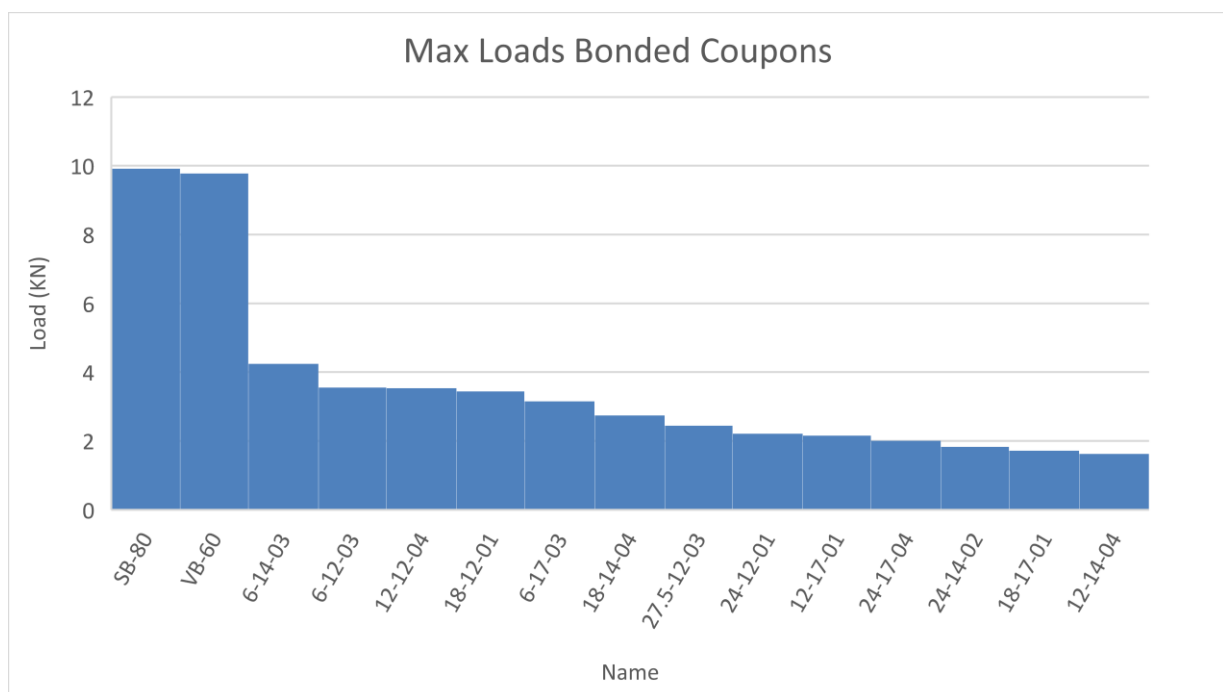
SB-60 has the highest normal stress from graph 17, with a stress of 106.37MPa. All specimens have similar paths to each other. The roughness measurements that can be seen in Table 14 show that it is not necessarily the coupon with the largest roughness that has the best results. Again, this is because of the bond thickness difference between iterations.

Table 14 – Roughness of Vapour Blasted coupons

	Roughness Virgin Material	Roughness Treated Area
VB 20	1.654	0.742
	2.453	0.742
VB 30	1.909	0.693
	2.794	0.672
VB 40	2.389	0.7
	1.883	0.702
VB 50	2.564	0.768
	3.05	0.724
VB 60	2.614	0.527
	2.082	0.493
VB 70	1.323	0.567
	3.084	0.572
VB 80	2.386	0.627
	1.451	0.603

8 Discussion and conclusion

Out of the bonded coupons, the most successful treatments were the shot blasted and vapour blasted treatments, with loads of 9.9kN and 9.78kN, respectively. They also had the strongest bond strength of the lot, with a strength of 14.46MPa and 15.15MPa respectively, compared to the manufacturer datasheet quoted value of 36.1MPa (3M, 1996). This value was not reached because the carbon fibre failed before the adhesive did. The manufacturer datasheet quoted a in plane shear stress of 112MPa, which both the shot blasted coupons and vapour blasted coupons did not exceed. However, this data was collected from tests done on untreated carbon fibre. The blasting of the material degraded the material and made it weaker, therefore the values of 107.88MPa for the shot blasted coupons and 106.37MPa were enough for the material to fail on its first ply. The max loads of all the bonded coupons can be seen in Graph 8.



Graph 18 – Max Loads Bonded Coupons

The improved performance of bonded joints introduces manufacturing drawbacks, most notably the need for controlled surface preparation and curing time, along with the energy required for the process and the increased difficulty in controlling the quality and joint consistency. However, it can be used alongside the mechanical fastening to increase the joint performance and the rivet can be used as a locating feature.

The single and double rivet specimens experienced only bearing and tear out stresses of the coupon and failed at lower loads in comparison to their hybrid counterparts. Once the adhesive was added to the joint, the stresses could be spread more evenly across the area. It was found that the hybrid coupons started to fail along the hole area, due to the presence of the rivets.

Plasma treatment was a novel idea which can increase dramatically the speed at which components can be bonded together, as it takes a fraction of the time in comparison to other surface treatments. It also has the added benefit of it being able to clean any organic matter from the specimen at the same time. The problem came when tensile testing the components, which were not giving out expected results. Previous work done at Lentus Composites with metallic components, shows that plasma treatment of components is very close to shot blasting, as seen in Graph 19. The plasma treated coupons from column 23 to 32 are consistently failing around the same loads as shot blasting. This kind of data casts serious doubts on the data collected from the CFRP plasma treated components talked about in this paper. It is believed that the root of the problem is incorrect material and bond thickness. Furthermore, larger exposure times to the plasma would have been adequate.

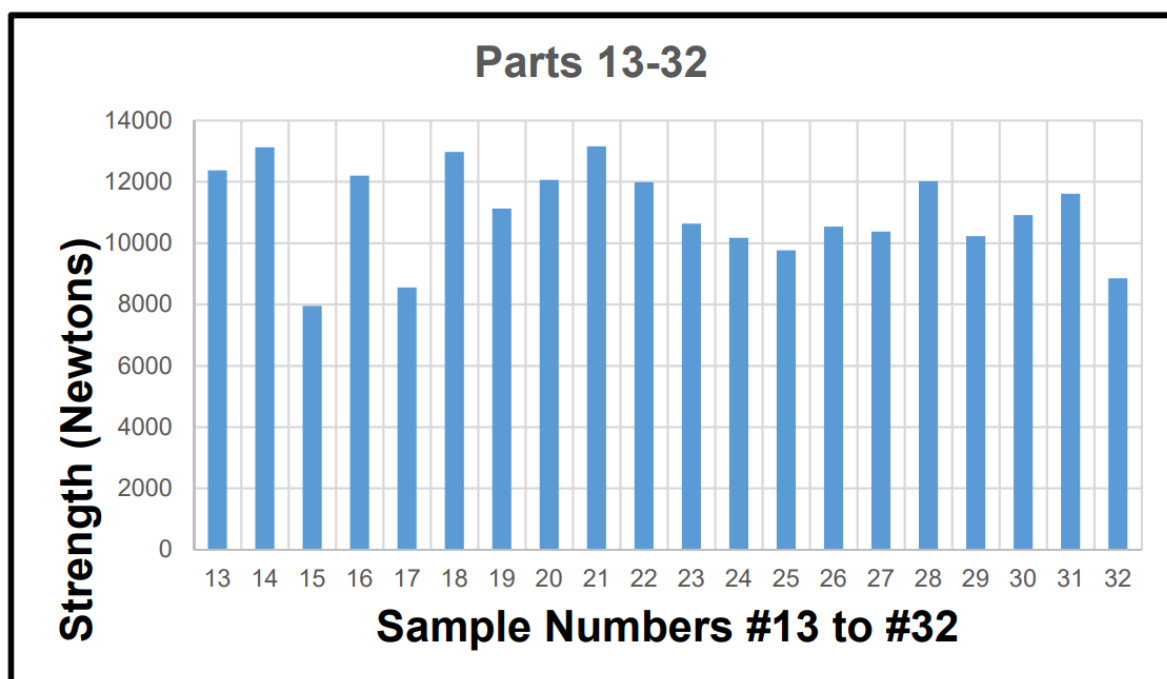


Figure 13: Test Results (Items #13 to #22 – standard grit blast. Items #23 to #32 Plasma treated))

Graph 19 – Shot blasted component 13 to 22 and plasma treated component 23 to 32. (Lentus Composites, 2020)

The max glue strength was achieved by the bonded coupons without the need of rivets. There is a drop in performance for the Double riveted hybrid specimens, due to the presence of those double holes and rivets which produce stress concentrations in that area. The strongest bond for the plasma treated coupon was achieved by the shortest distance nozzle to coupon of 6mm and a conveyor belt speed of 14m/min. Although it didn't have the highest surface energy of the group, the distance provided a good spread of the plasma across the area to be treated.



In all, the project successfully found that using adhesives instead of rivets is a viable solution, while the correct procedures are undertaken, and the bond line thickness is controlled in the best possible way. Plasma treatment has great potential - from the surface energy measurements it can be seen that untreated carbon fibre has a Surface Energy of 34mN/m, while the highest level of energy achieved when plasma treated elevated that number to 71mN/m with only an exposure time of 0.25seconds per mm. Unfortunately, the bond line thickness hindered the results from the plasma treated specimens.

9 Further Work

The following further work can be done:

- Build another jig which consistently gives accurate bond thicknesses.
- Further testing of plasma treated coupons with much larger exposure times.
- Produce all coupons in the autoclave at the same time to counteract any change in coupon thickness.
- Look at the purchase of a Mobile Surface Analyzer, which can take an accurate reading of the surface energy for any component in a space of minutes. This takes away the need to use a camera with a macro lens, which if put at an incorrect angle will give wrong data.

10 Pandemic Impact

Contact angles could not be measured for calculating accurate surface free energy of a solid, Dyne pens had to be used instead which do not give an exact result.

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12 Appendix – A Project Management

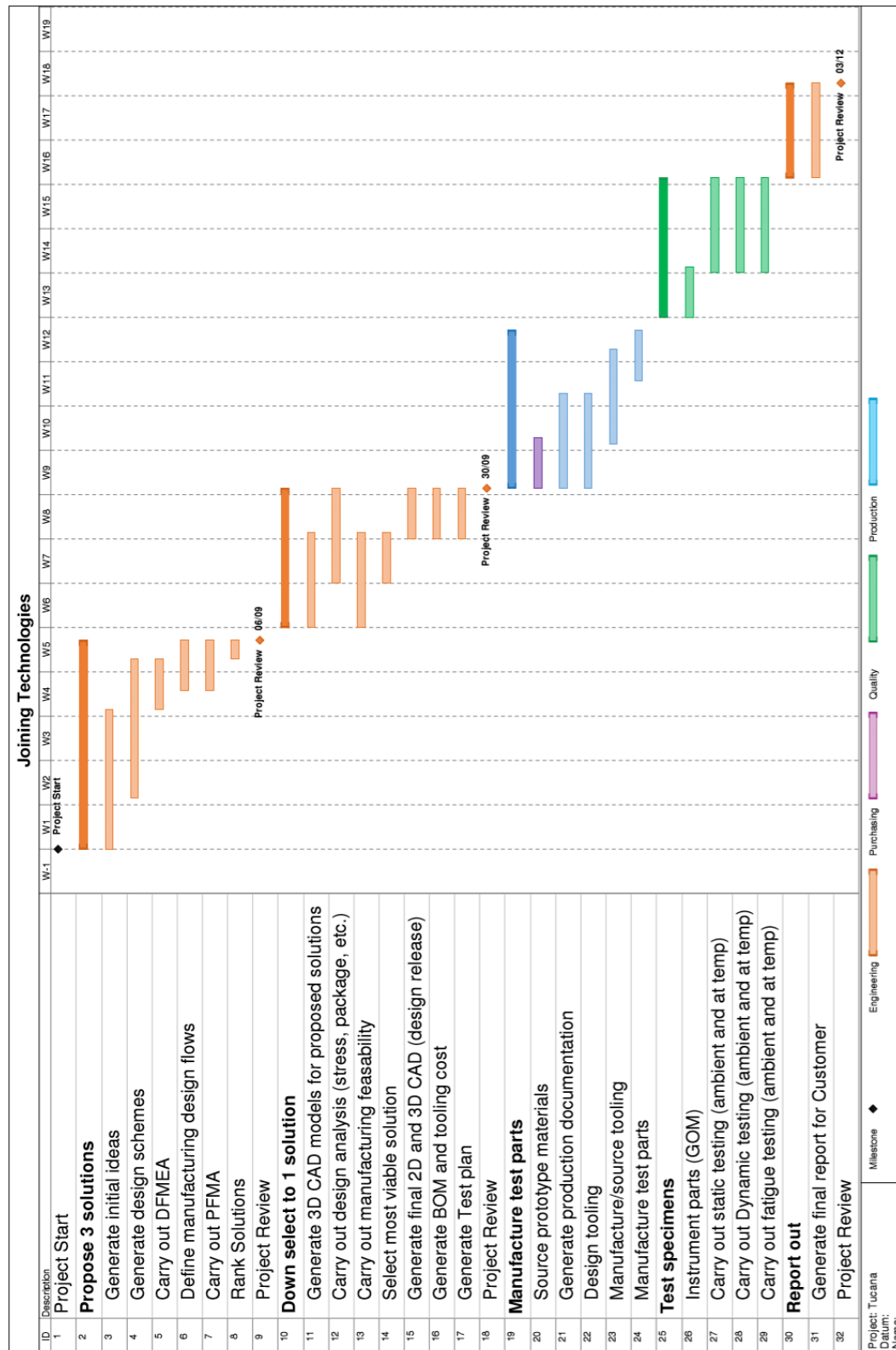


Figure A- 1 – First half of project Gantt Chart

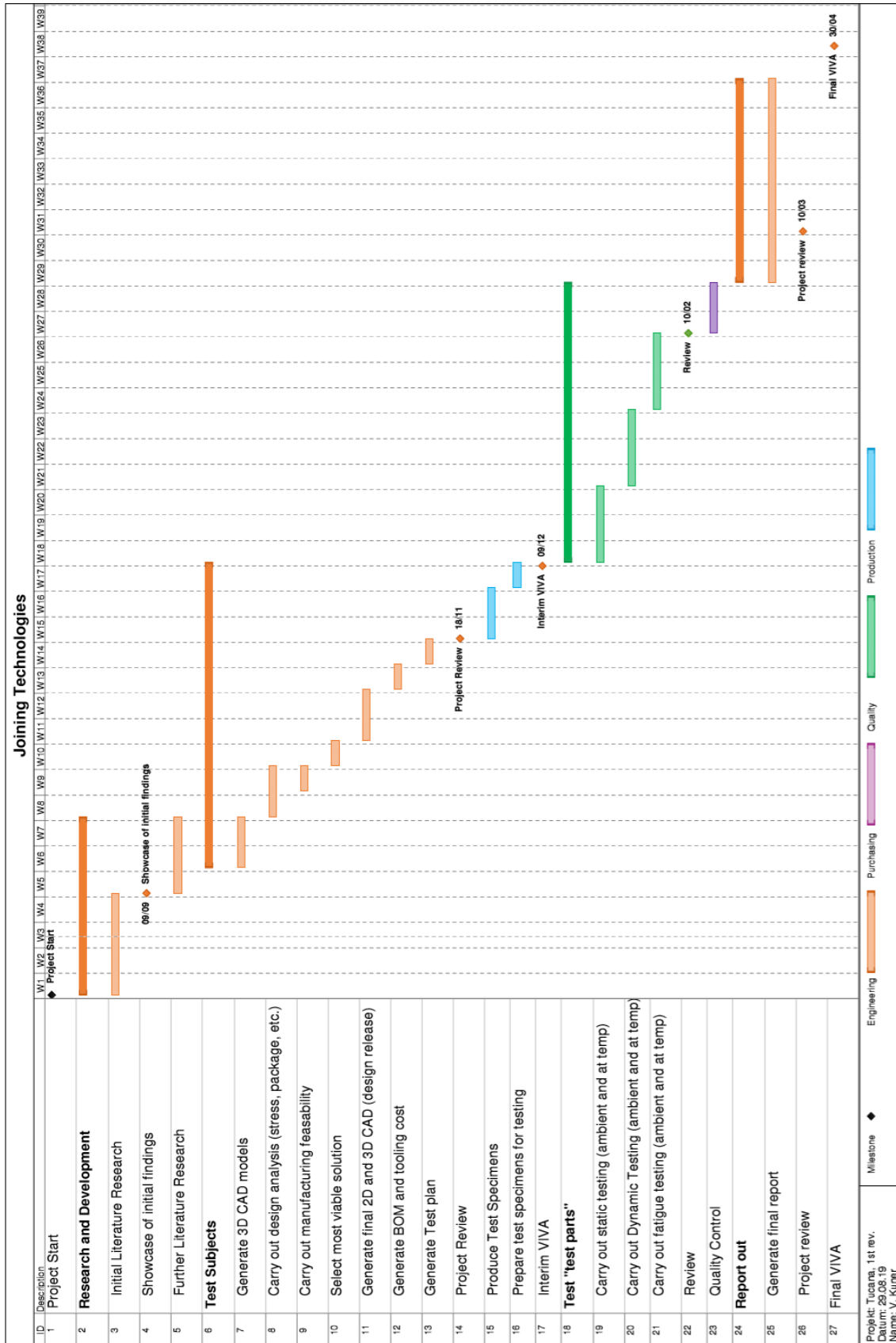


Figure A- 2 – Overall Project Gantt Chart



Joining Technologies

UWTSO

Vijay Kuner

Project Start: 27/01/2020

Display Week: 1

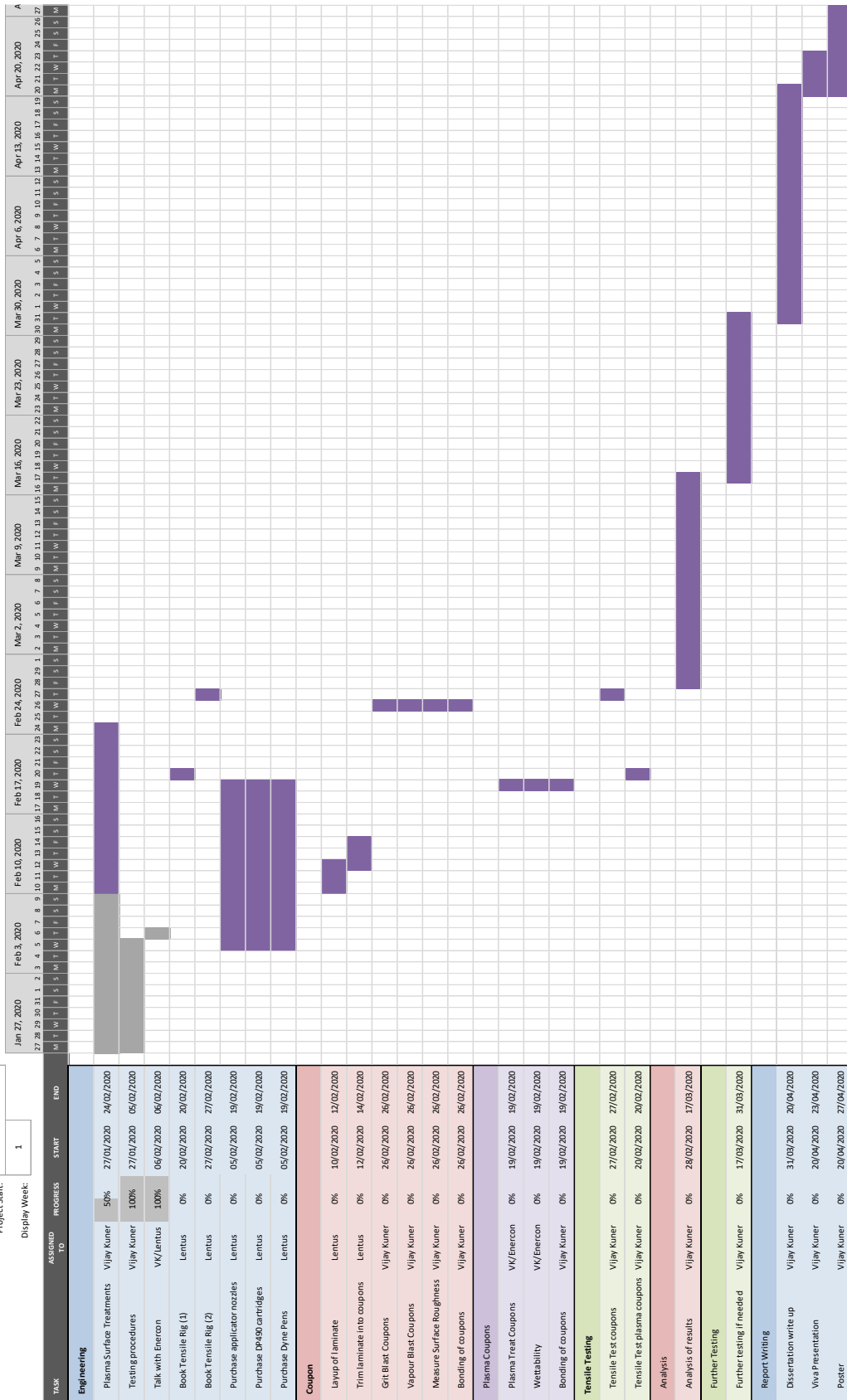


Figure A-3 – Second half of project Gantt Chart



13 Appendix – B: Engineering Documents

13.1 Traveller

BUILD TO PRINT TRAVELLER Page 1 of 5 PRODUCTION ORDER

LENTUS COMPOSITES		DOCUMENT DETAILS	
START DATE		CUSTOMER NUMBER	
11/10/2019		LCBD NUMBER	
PRODUCTION ORDER		CUSTOMER DRAWING NUMBER	
48271		TRAVELLER DOCUMENT NUMBER	
		CUSTOMER PART NAME	TESTING VISAY
		LAY UP BOOK NUMBER	
		PROJECT CONTACT(S)	
		Daniel Brooks, Susannah Haines, Rhian Nathanson, Viktoria Filippova	

STEP	OP	DETAILS	PASS	STAMP	DATE
TOOL PREPARATION	A	Locate tooling;	Number of sub-pieces	2	
		1 x Tool Assembly	Customer Tool Drawing Number		
			Customer Tool Number - Part 1	Flat sheet	
			Customer Tool Number - Part 2	Flat sheet	
	B	Are the tools the correct numbers as above?	PASS / FAIL		
	C	Check all tooling for any signs of damage - Stop and report if any issues found	PASS / FAIL		
	D	Is the tool new? If YES go to E	YES / NO		
	E	Is it sanded and clean?	YES / NO		
	F	Tick one box per coat (number depends on tool material)			
	F	Seal the tool according to SOP LC001-0111-0032	PASS / FAIL		
	When sealed go to G				
G	Tick one box per coat (number depends on tool material)				
G	Release the tool according to SOP LC001-0111-0040	PASS / FAIL			
H	Verify that tool has been correctly prepared	PASS / FAIL			
I	Final Sign off: All process complete and conforming?	PASS / FAIL			

ENSURE PROCESS CONTROLLED UNDER FOD & 6S

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Figure A- 4 – Traveller 1



BUILD TO PRINT TRAVELLER

Page 2 of 5

PRODUCTION ORDER

STEP	OP	DETAILS	PASS	STAMP	DATE	
CUT KIT	-	Chose an appropriate section "Machined kit" or "Supplied kit"	✓	AW	11/10	
MACHINED CUT KIT	A	Nest name:				
	B	Mat.#	Material Description	SAP	GRN	QTY
		1		900-000137	1767	2.9
		2				
		3				
	C	Cut kit is stored in labelled sealed bag in freezer	PASS / FAIL	N/a		
	D	Remove bagged kit from freezer	Record Time:	:		
	E	Start Laminating	Record Time:	:		
	F	Check kit has been out of freezer for minimum 6 hours before unsealing bag and laminating	PASS / FAIL	N/a		
	G	Final Sign off: All process complete and conforming?	(PASS) FAIL	✓	AW 11/10	
SUPPLIED KIT	A	Work Order Number				
	B	Confirm lay up manual matches number on Page 1	PASS / FAIL			
	C	Kit check with lay up book - all plies present and conforming?	PASS / FAIL			
	D	Cut kit is stored in labelled sealed bag in freezer	PASS / FAIL			
	E	Remove bagged kit from freezer	Record Time:	:		
		Check kit has been out of freezer for minimum 6 hours before unsealing bag and laminating	PASS / FAIL			
	F	Start Laminating	Record Time:	:		
	G	Final Sign off: All process complete and conforming?	PASS / FAIL			

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Figure A- 5 – Traveller 2



BUILD TO PRINT TRAVELLER

Page 3 of 5

PRODUCTION ORDER

STEP	LAY UP				PASS	STAMP	DATE
	OP NUMBER	MATERIAL	PLY LOCATION	ORIENTATION			
LAMINATING	01	900-000137	-	45°	✓	<i>tan</i>	
	02	-	-	90°	✓	<i>tan</i>	
	03	-	-	45	✓		
	04	-	-	90	✓		
	05	-	-	45	✓		
	06	-	-	90	✓		
	07	-	-	45	✓		
	08	-	-	90	✓		
	09	-	-	45	✓		
	10	-	-	90	✓		
	11	-	-	45°	✓		
	12	-	-	90	✓		
	13	-	-	45	✓		
	15	Laminate PO Number Label in visible location					
Final Sign off: All process complete and conforming?				PASS / FAIL			
ENSURE PROCESS CONTROLLED UNDER FOD & 6S							
STEP	OP	DETAILS			PASS	STAMP	DATE
BAG	A	Apply release film.			PASS / FAIL		
	B	Apply breather fabric.			PASS / FAIL		
	C	Fit vacuum bag.			PASS / FAIL		
	D	Vacuum Check Bag			PASS / FAIL		
	E	Final Sign off: All process complete and conforming?			PASS / FAIL	✓ <i>[Signature]</i>	
ENSURE PROCESS CONTROLLED UNDER FOD & 6S							

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Figure A-6 – Traveller 3

BUILD TO PRINT TRAVELLER

Page 4 of 5

PRODUCTION ORDER

STEP	OP	DETAILS					PASS	STAMP	DATE
CURE	A	Place bagged part in Autoclave	Autoclave	Italmatic	LBBC	Maroso			
	B	Connect Vacuum Lines & Thermocouple	Vac Port #	3					
			Thermocouple #	✓					
	C	Perform bag vacuum check in Autoclave			PASS / FAIL			OP 35	15 OCT 2019
	D	Load cure programme	Programme Name From Lay up Manual			Reph Wing Curs			
			Correct Programme Loaded?			PASS / FAIL		OP 35	15 OCT 2019
	E	Run cure program	Time Started			09 : 50			
	F	Final Sign off: All process complete and conforming?			PASS / FAIL			OP 35	15 OCT 2019

ENSURE PROCESS CONTROLLED UNDER FOD & 6S

STEP	OP	DETAILS					PASS	STAMP	DATE
CURE CHECK	A	Compare cure log to programme master	Vacuum Vented	PASS / FAIL					
			Overall Cure	PASS / FAIL					
	B	Verify that cure was correct.			PASS / FAIL				
	C	Final Sign off: All process complete and conforming?			PASS / FAIL			OP 35	15 Oct 19

ENSURE PROCESS CONTROLLED UNDER FOD & 6S

STEP	OP	DETAILS					PASS	STAMP	DATE
DEMOULD PART	A	Remove bag, break out part and put valve in appropriate place			PASS / FAIL				
	B	Check part for signs of damage. Raise any concerns with Engineering			PASS / FAIL				
	C	Check tooling for signs of damage. Raise any concerns with Engineering			PASS / FAIL				
	D	Final Sign off: All process complete and conforming?			PASS / FAIL				

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Figure A- 7 – Traveller 4



BUILD TO PRINT TRAVELLER

Page 5 of 5

PRODUCTION ORDER

STEP	OP	DETAILS	PASS	STAMP	DATE
TRIM / ASSY	A	Trim part to engineering drawing.	PASS / FAIL		
	B	All fittings present and correct to engineering drawing?	PASS / FAIL OR N/A		
	C	Final Sign off: All process complete and conforming?	PASS / FAIL		
ENSURE PROCESS CONTROLLED UNDER FOD & 6S					

STEP	OP	DETAILS	PASS	STAMP	DATE
QUALITY & INSPECTION	A	Correct revision of drawing used to inspect part?	PASS / FAIL		
	B	Measuring equipment calibrated?	YES / NO		
	C	Visually inspect part to engineering drawing, customer requirements and/or Lentus Composites visual standards.	PASS / FAIL		
	D	Measure all critical to quality features specified on engineering drawing and/or CAD model.	PASS / FAIL		
	E	Requirements met?	PASS / FAIL		
	F	Complete Inspection Report.	PASS / FAIL		
	G	Inspection report signed and saved in appropriate directory?	PASS / FAIL		
	H	Review Generic Traveller. Is it complete?	YES / NO		
	I	Final Sign off: All process complete and conforming?	PASS / FAIL		
ENSURE PROCESS CONTROLLED UNDER FOD & 6S					

Document Release
LD001-0293-0071 Issue 01
Traveller - Build to Print (Blank)

Engineering

Stéphane Hello
2019.04.18
17:26:18
+0100'

Quality

Niall O'Callaghan
2019.04.17
15:00:04 +0100'

Production

Rhian
Nathanson
2019.04.17
11:00:00 +0100'

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Figure A- 8 – Traveller 5

13.2 MBI

	M ANUFACTURING B UILD I NSTRUCTION	NUMBER	*	KEY
		DESCRIPTION	COUPON ADHESIVE SHEAR TEST	 Quality
		AREA	ASSEMBLY ROOM	 Safety
				 Ease

PURPOSE

This document defines a standard methodology for producing and conducting a Adhesive shear test on coupons.

SCOPE

Applies to the all processes for adhesive shear tests, unless otherwise specified

RESPONSIBILITIES

It is the responsibility of the Manufacturing Engineer to ensure that this document is kept up to date.
 It is the responsibility of the Production Manager to ensure that this document is followed.
 It is the responsibility of the Operator to raise any improvements or concerns within this document.

REVISION HISTORY

ISSUE	DESCRIPTION	AUTHOR	DATE	ENGINEERING	PRODUCTION	QUALITY
01	FIRST ISSUE	V KUNER	05/02/2020			

Figure A- 9 – MBI title page

CONTENTS

PURPOSE.....	1
SCOPE	1
RESPONSIBILITIES.....	1
REVISION HISTORY	1
CONTENTS.....	2
TOOLS REQUIRED.....	3
RELATED DOCUMENTS	3
SHEAR ADHESION TEST TO ASTM D5868 STANDARD	4
COUPON PROCESS:	5
PHASE 1: Coupon	5
PHASE 2: SHEAR TEST	14
PHASE 3: ANALYSIS	18

Figure A- 10 – Contents of MBI

PROCEDURE				
OPERATION	STEP DESCRIPTION	CARE POINT	OPERATION DESCRIPTION	IMAGE / SCHEMATIC
OP10	PPE		Appropriate PPE shall be worn throughout the assembly process: - Protective eye wear and steel toe capped boots <u>at all times</u> - Protective latex/nitrile gloves when handling adhesive	
OP20	Tool Prep	☒	Ensure two steel plates or two smooth carbon fibre plates has been correctly sealed and released for lamination in accordance with D1.	
OP30	LAMINATE	☒	Laminate following D7	
* COUPON ADHESIVE SHEAR TEST UNCONTROLLED WHEN PRINTED IF IN DOUBT - ASK QMF 31 5 of 18 QMF 31				

Figure A- 11 – Snip of content that can be found in MBI.

14 Appendix C – Graphs

14.1 Hybrid Single Rivet

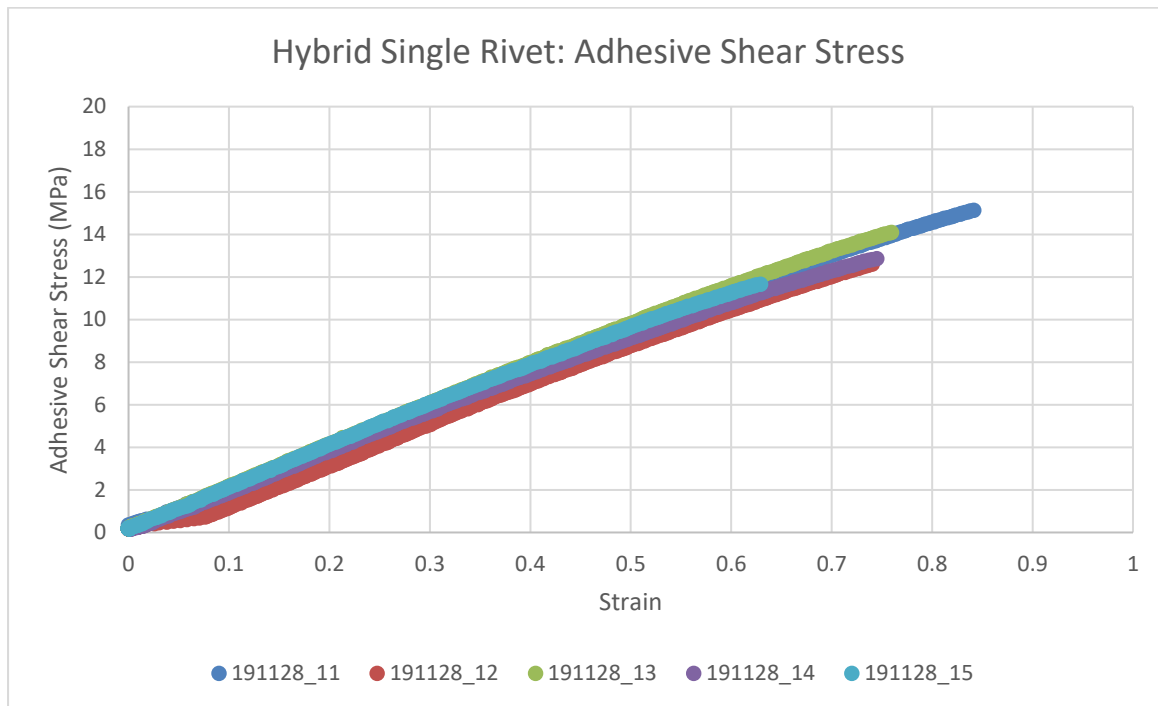


Figure A- 12 – Hybrid Single Rivet: Adhesive Shear Stress

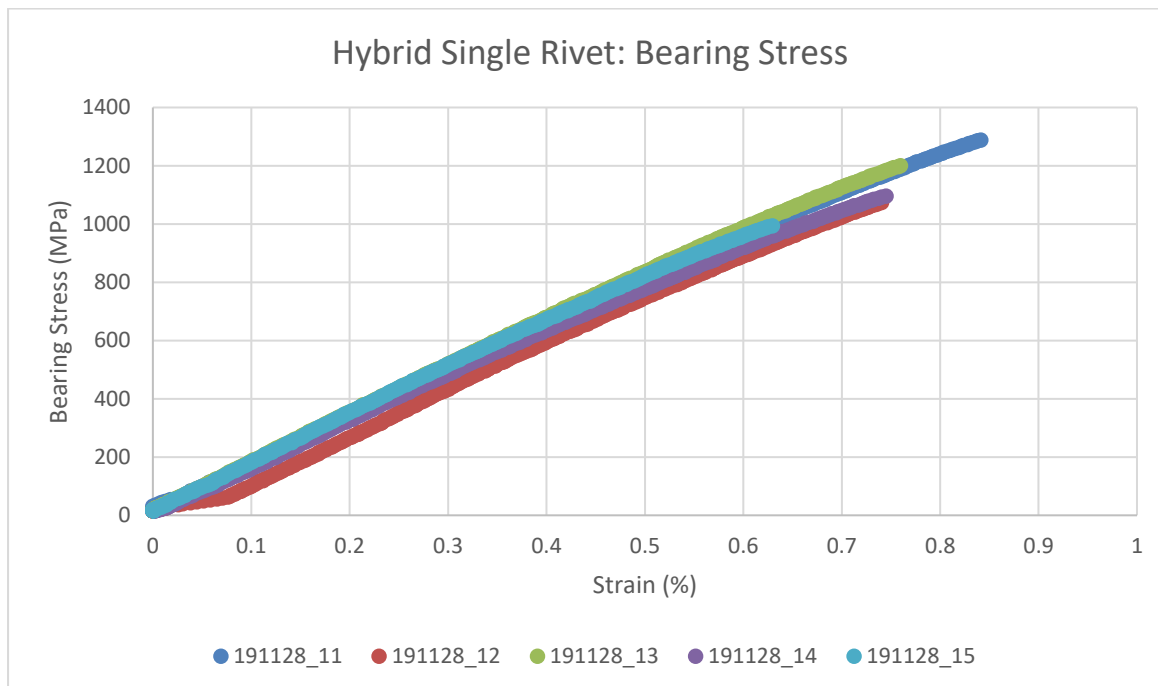


Figure A- 13 - Hybrid Single Rivet: Bearing Stress

14.2 Hybrid double rivet

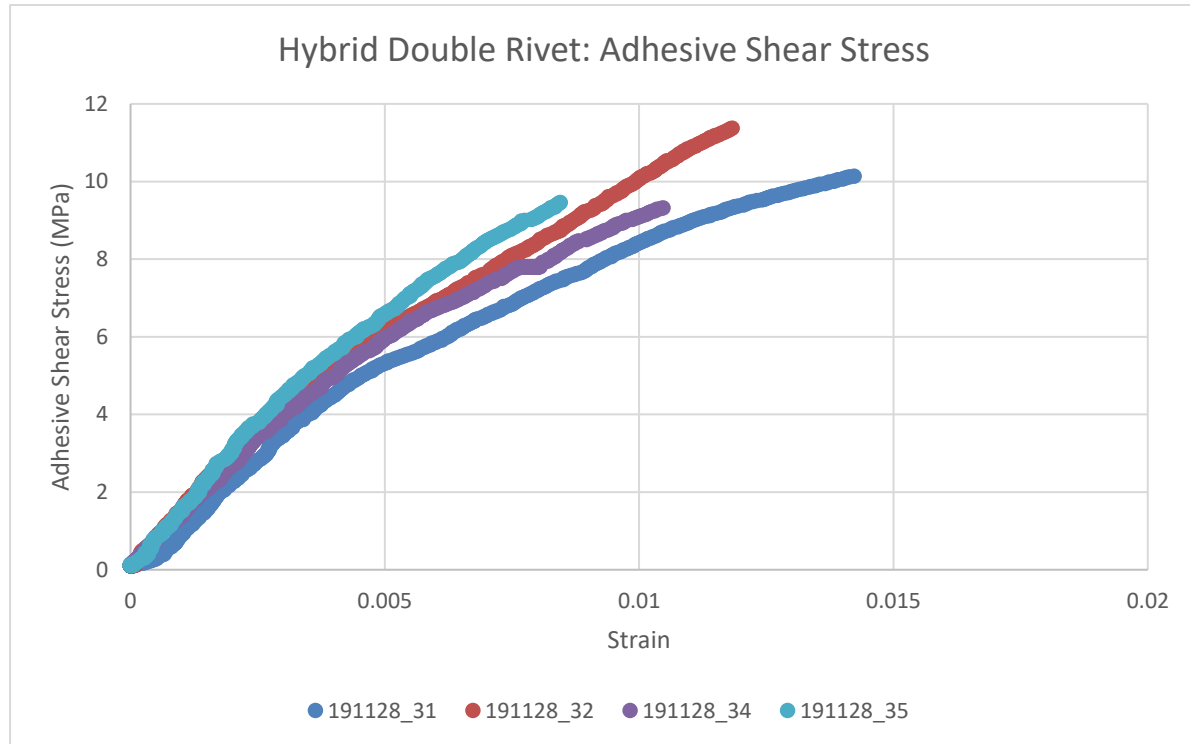


Figure A- 14 - Hybrid Double Rivet: Adhesive Shear Stress

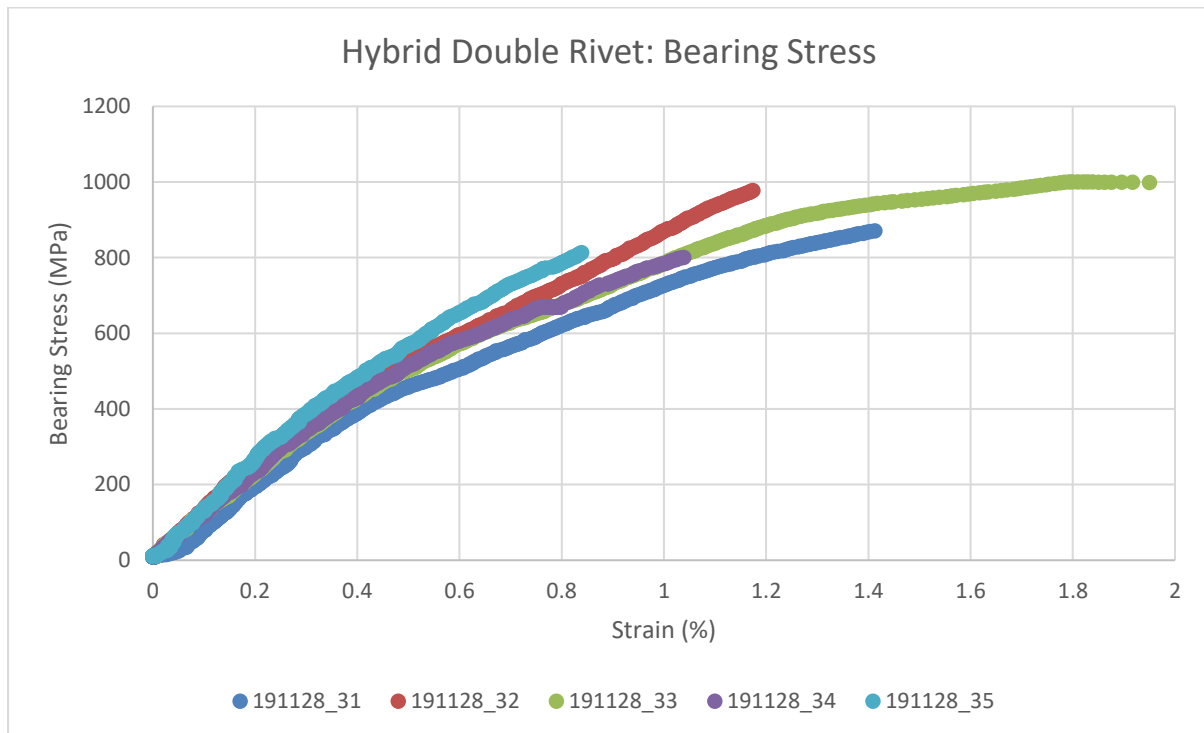


Figure A- 15 - Hybrid Double Rivet: Bearing Stress

14.3 Plasma Treated

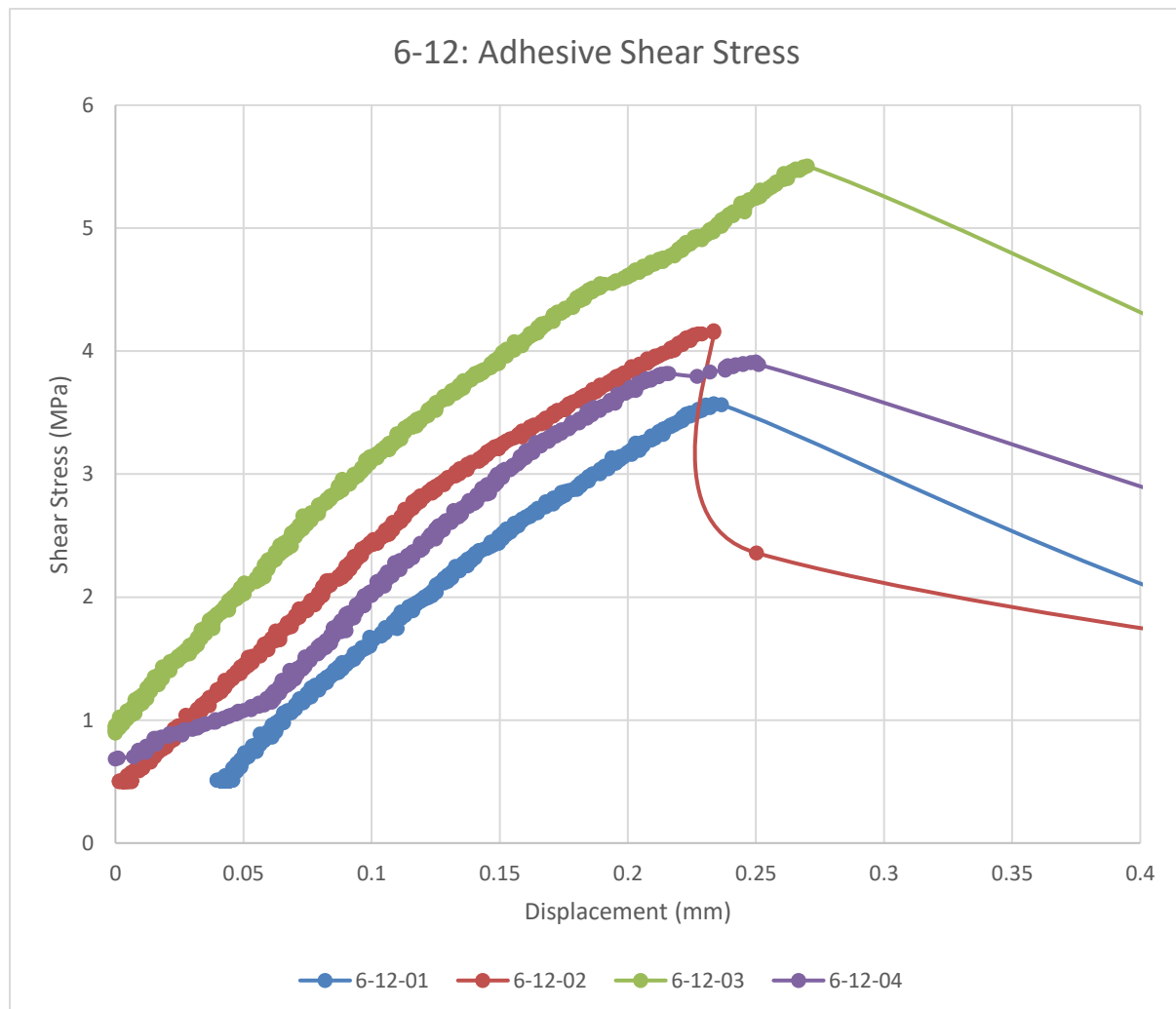


Figure A- 16 - 6-12: Adhesive Shear Stress

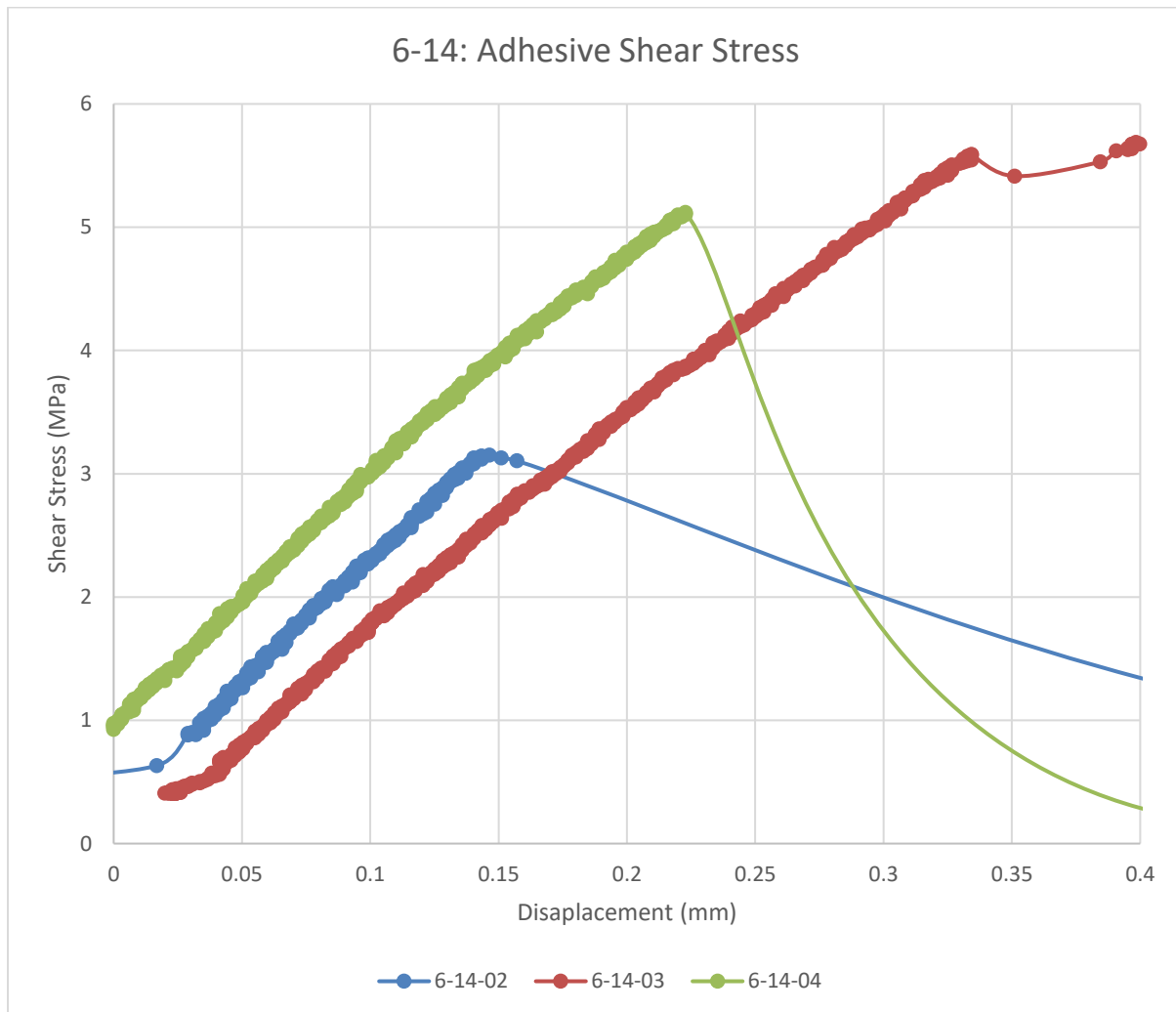


Figure A- 17 - 6-14: Adhesive Shear Stress

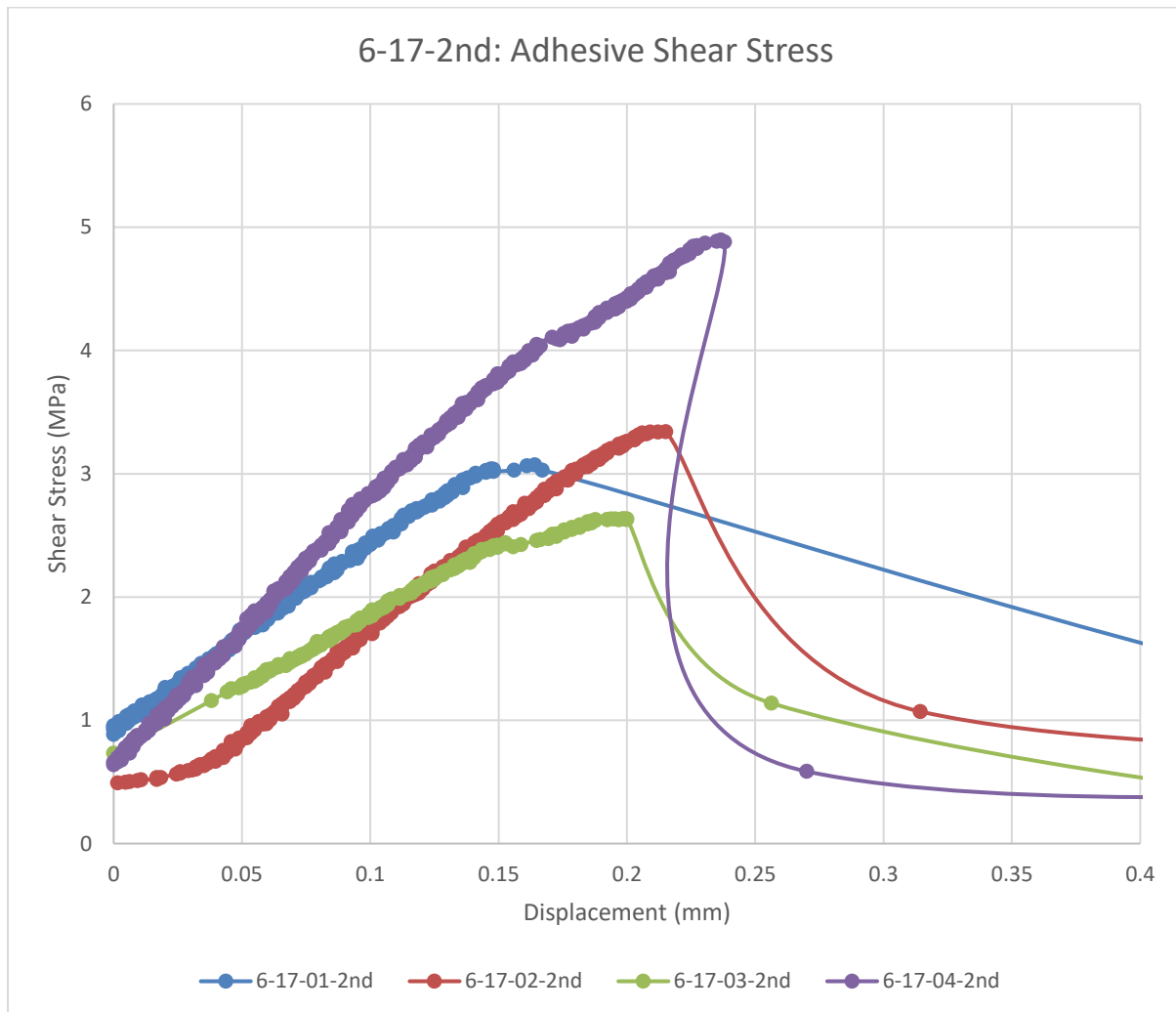


Figure A- 18 - 6-17-2nd: Adhesive Shear Stress

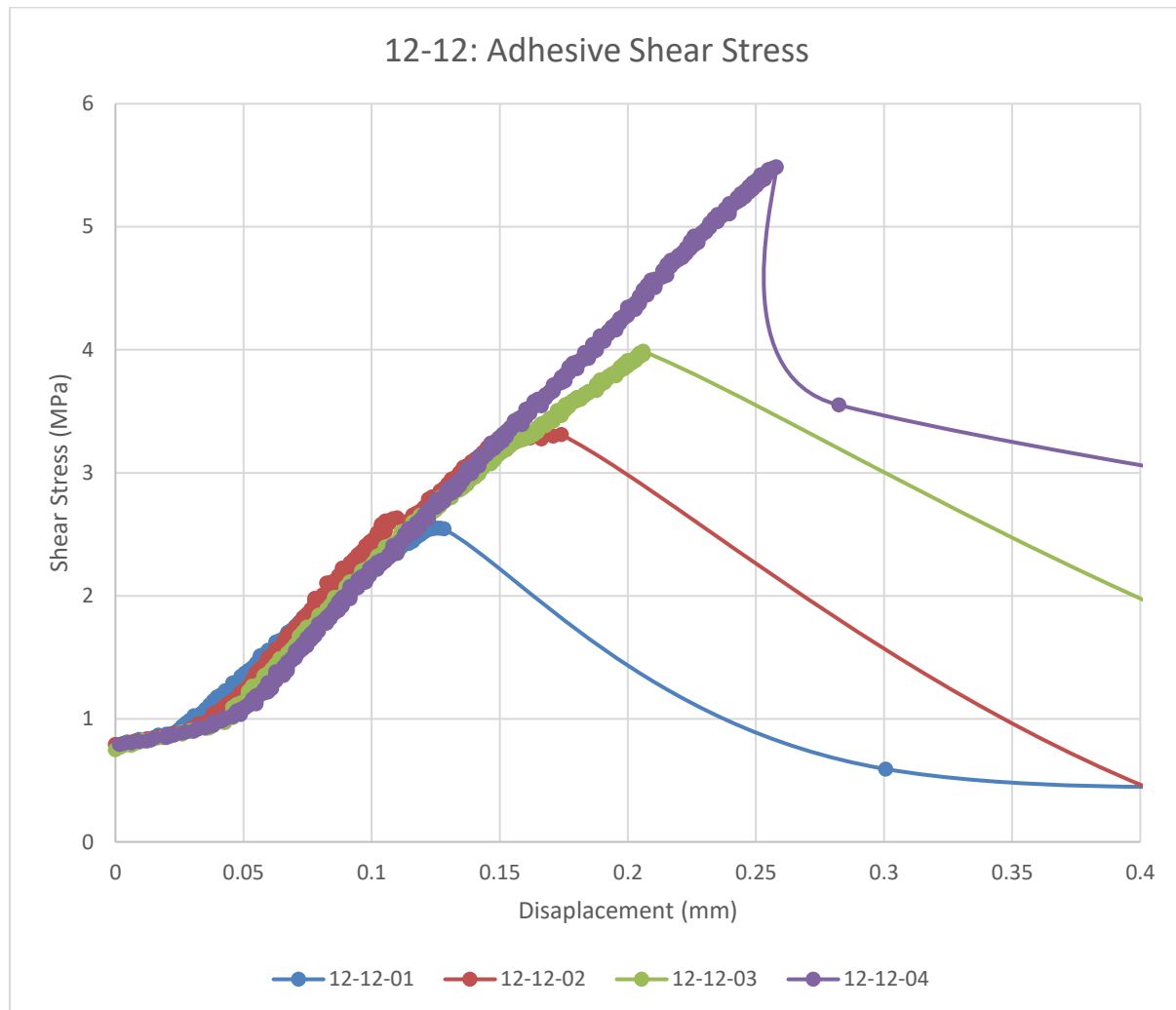


Figure A- 19 - 12-12: Adhesive Shear Stress

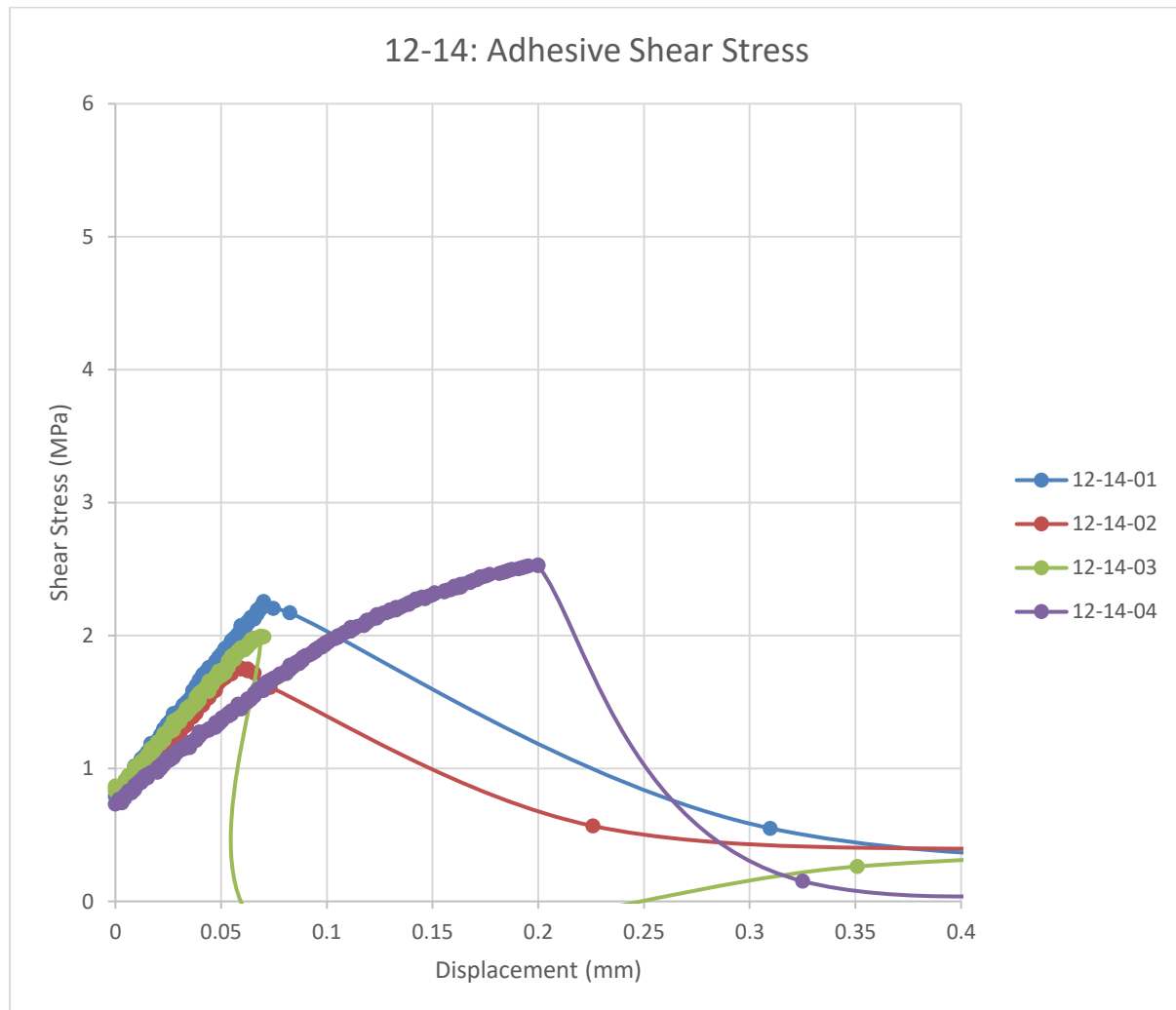


Figure A- 20 - 12-14: Adhesive Shear Stress



Figure A- 21 - 12-17: Adhesive Shear Stress

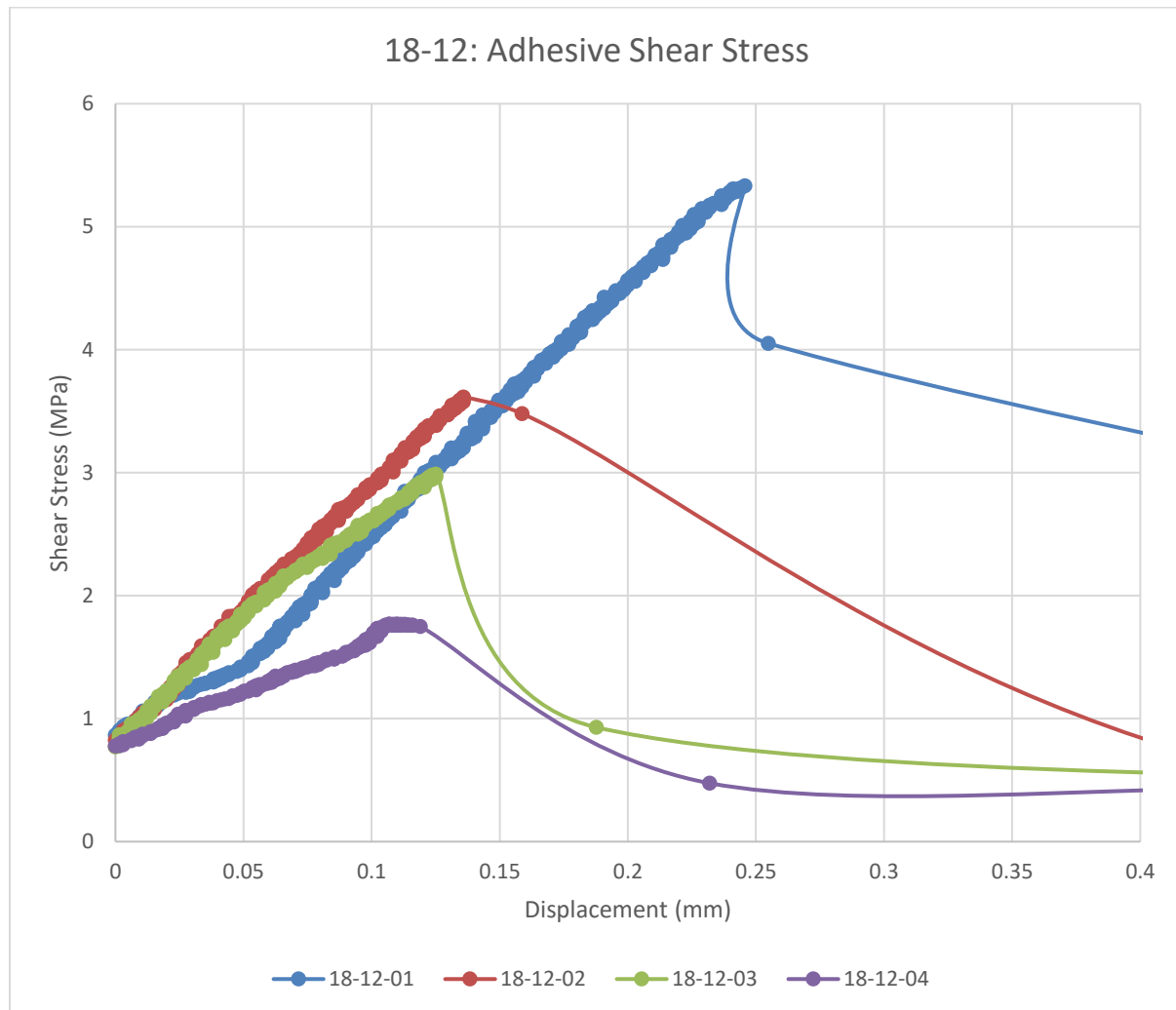


Figure A- 22 - 18-12: Adhesive Shear Stress

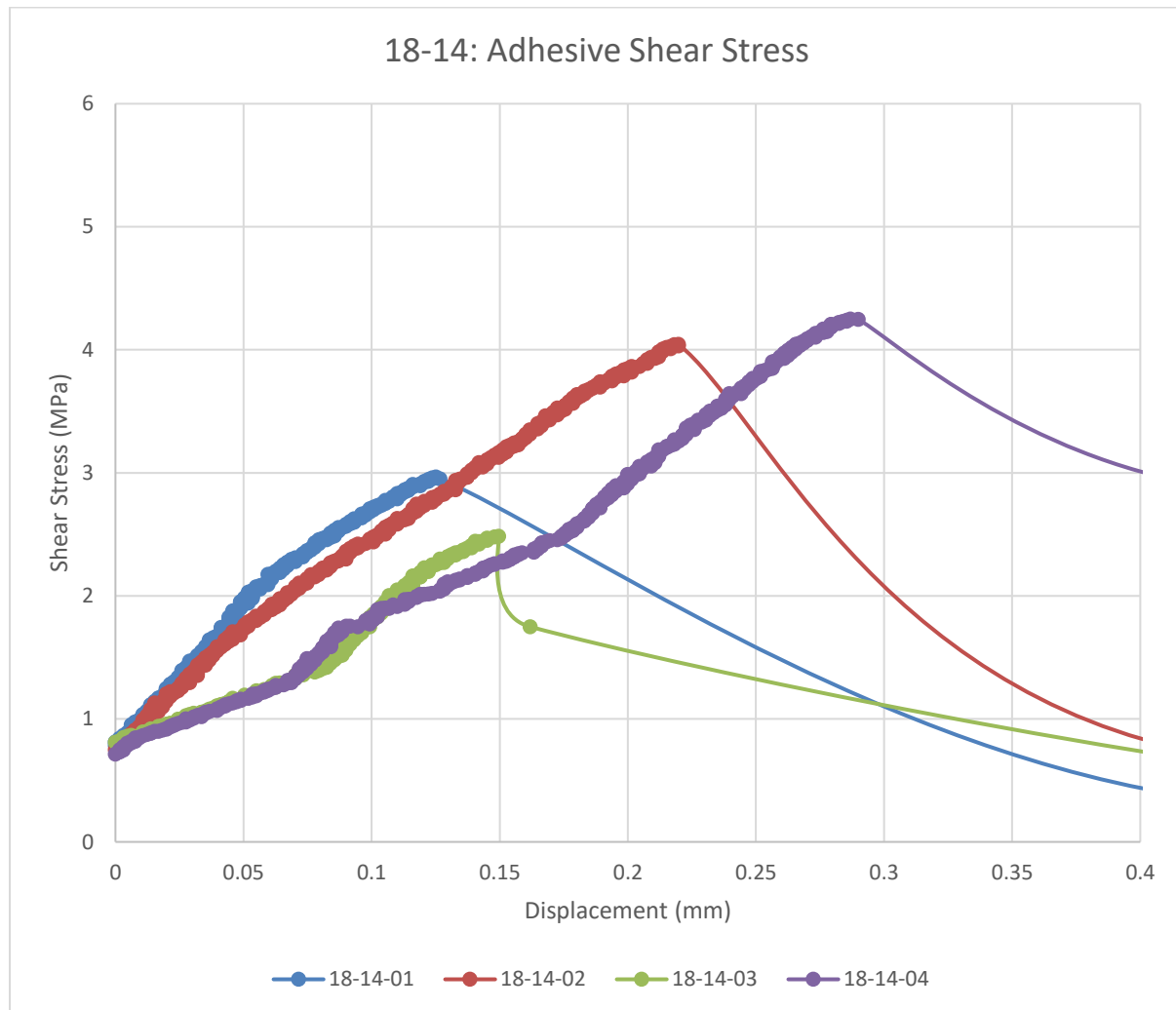


Figure A- 23 - 18-14: Adhesive Shear Stress

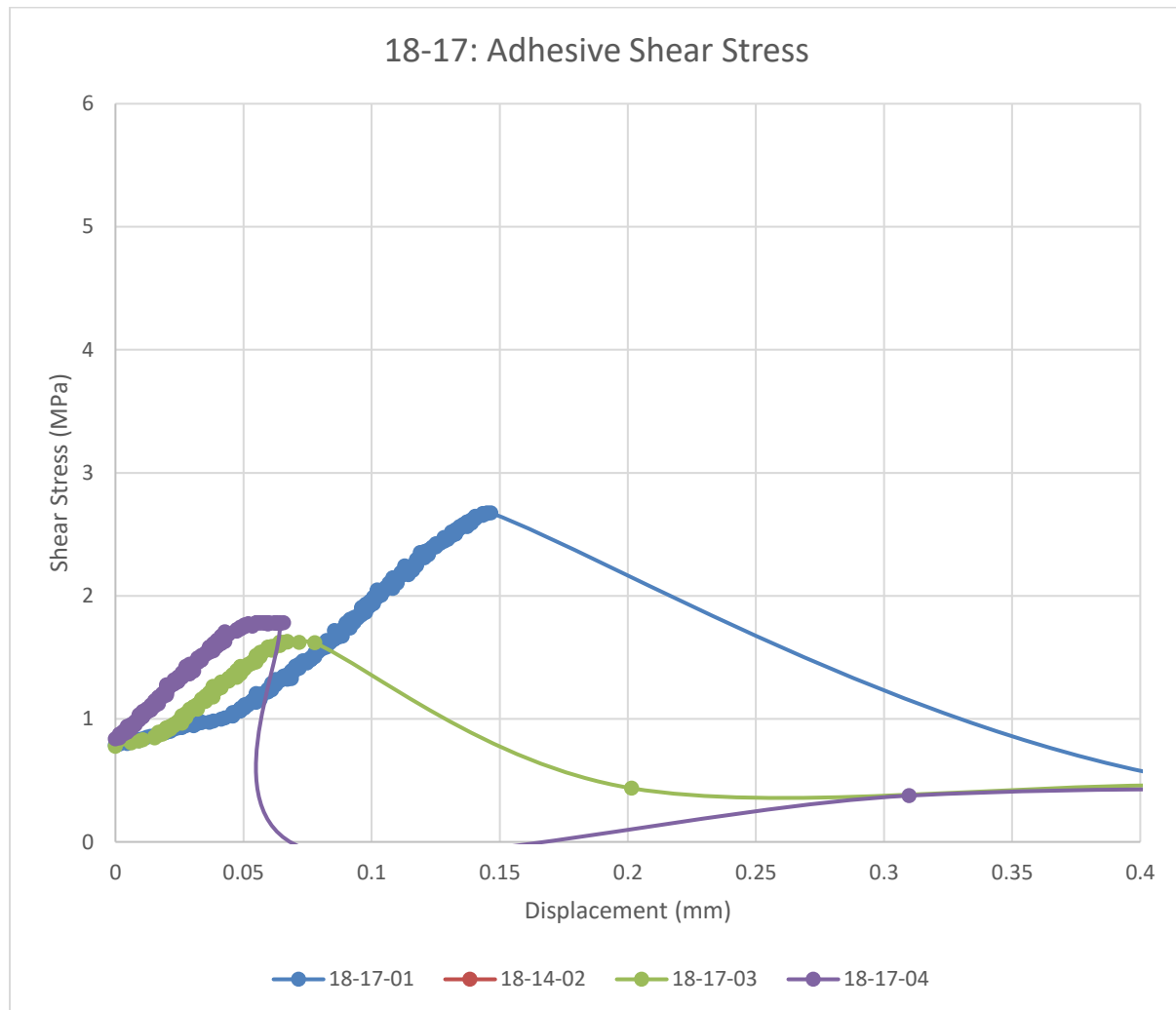


Figure A- 24 - 18-17: Adhesive Shear Stress

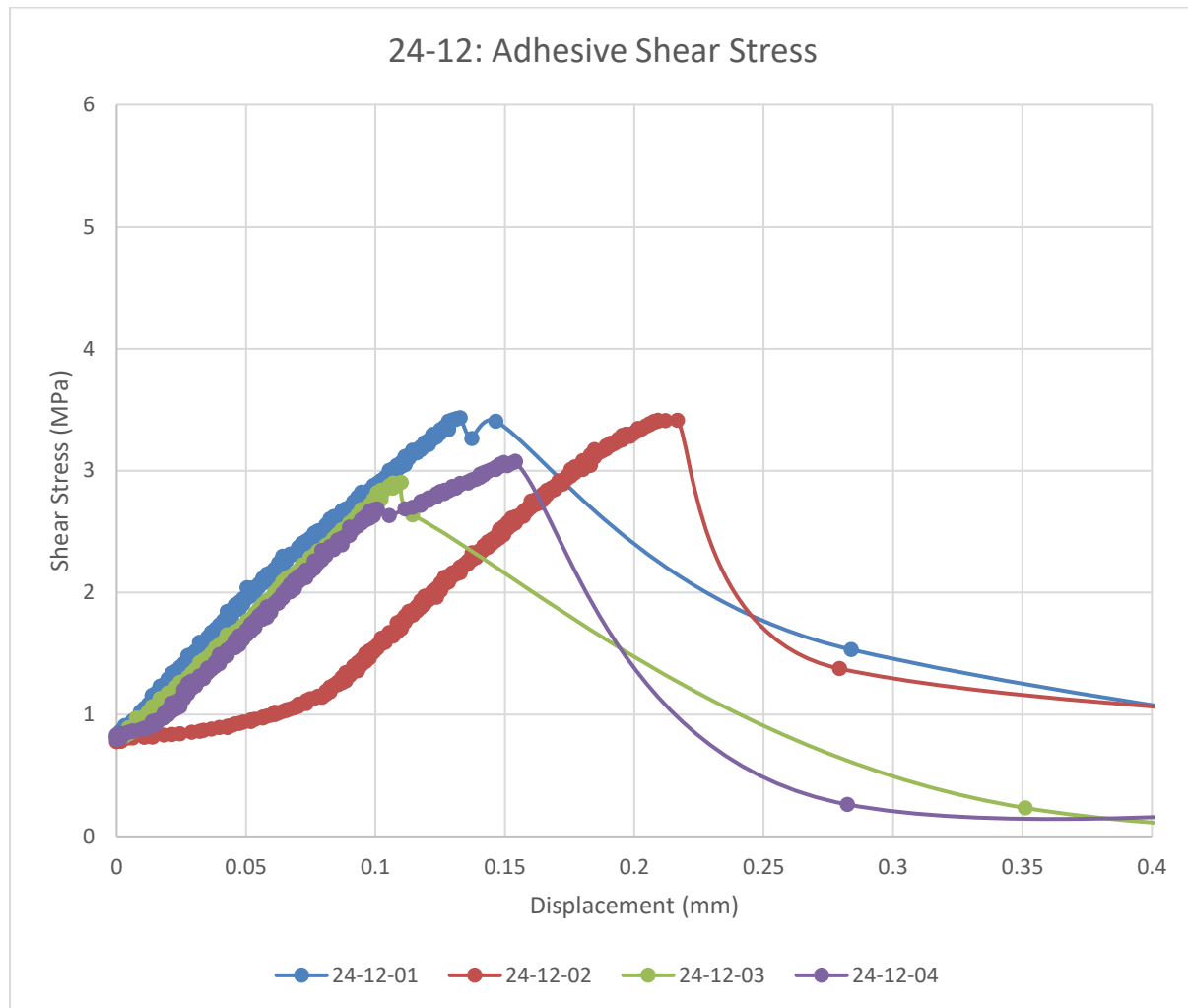


Figure A- 25 - 24-12: Adhesive Shear Stress

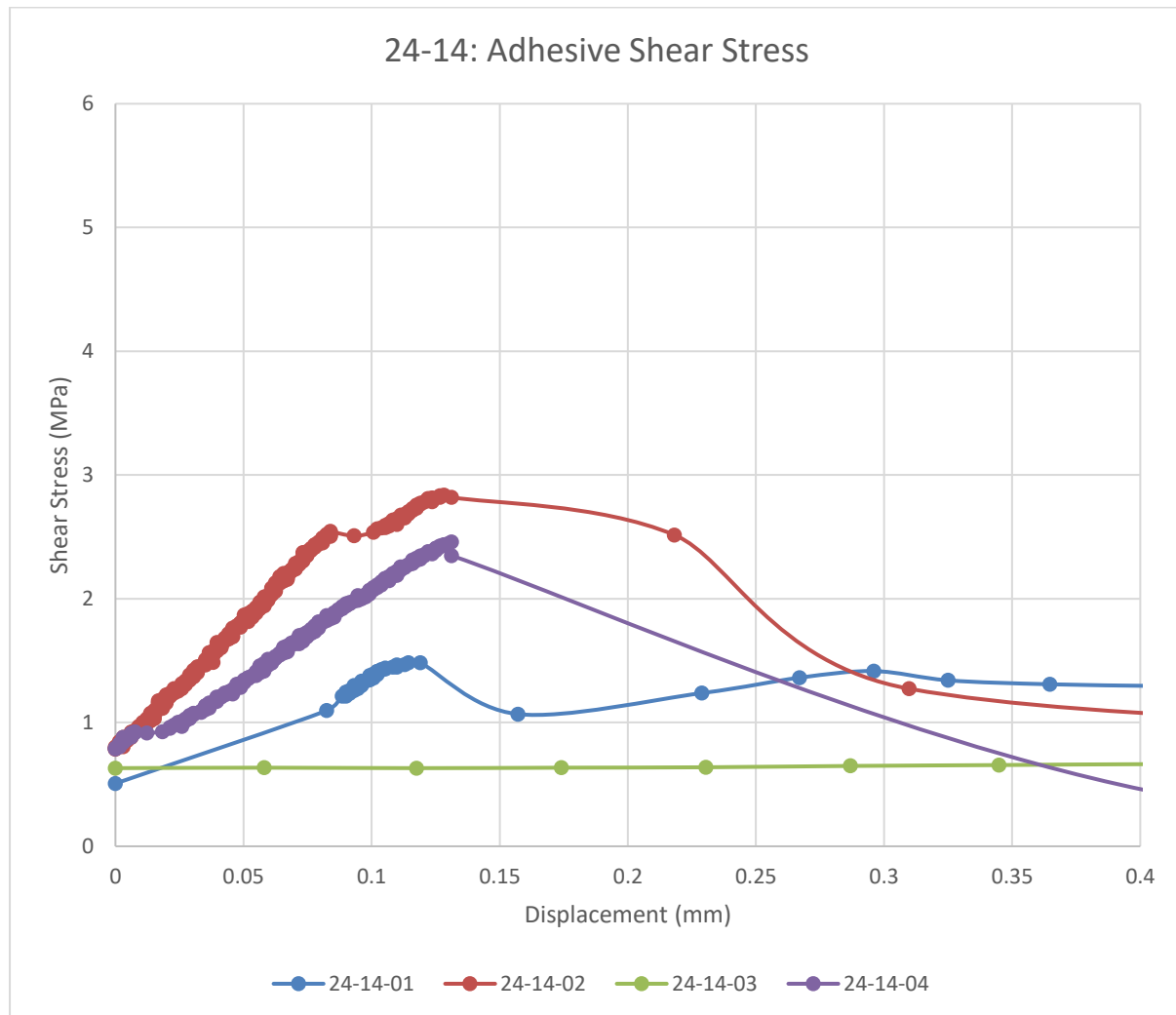


Figure A- 26 - 24-14: Adhesive Shear Stress

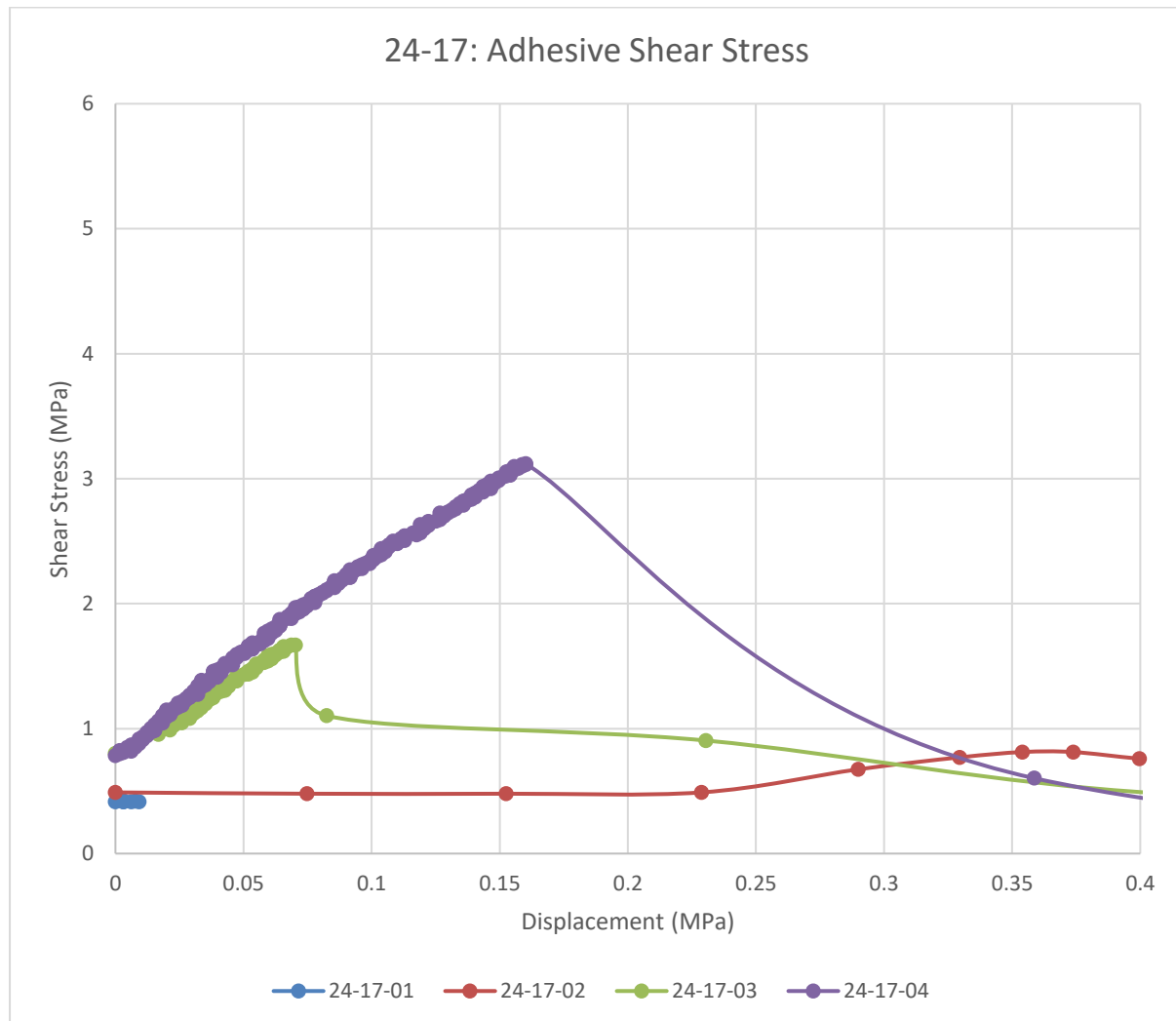


Figure A- 27 - 24-17: Adhesive Shear Stress

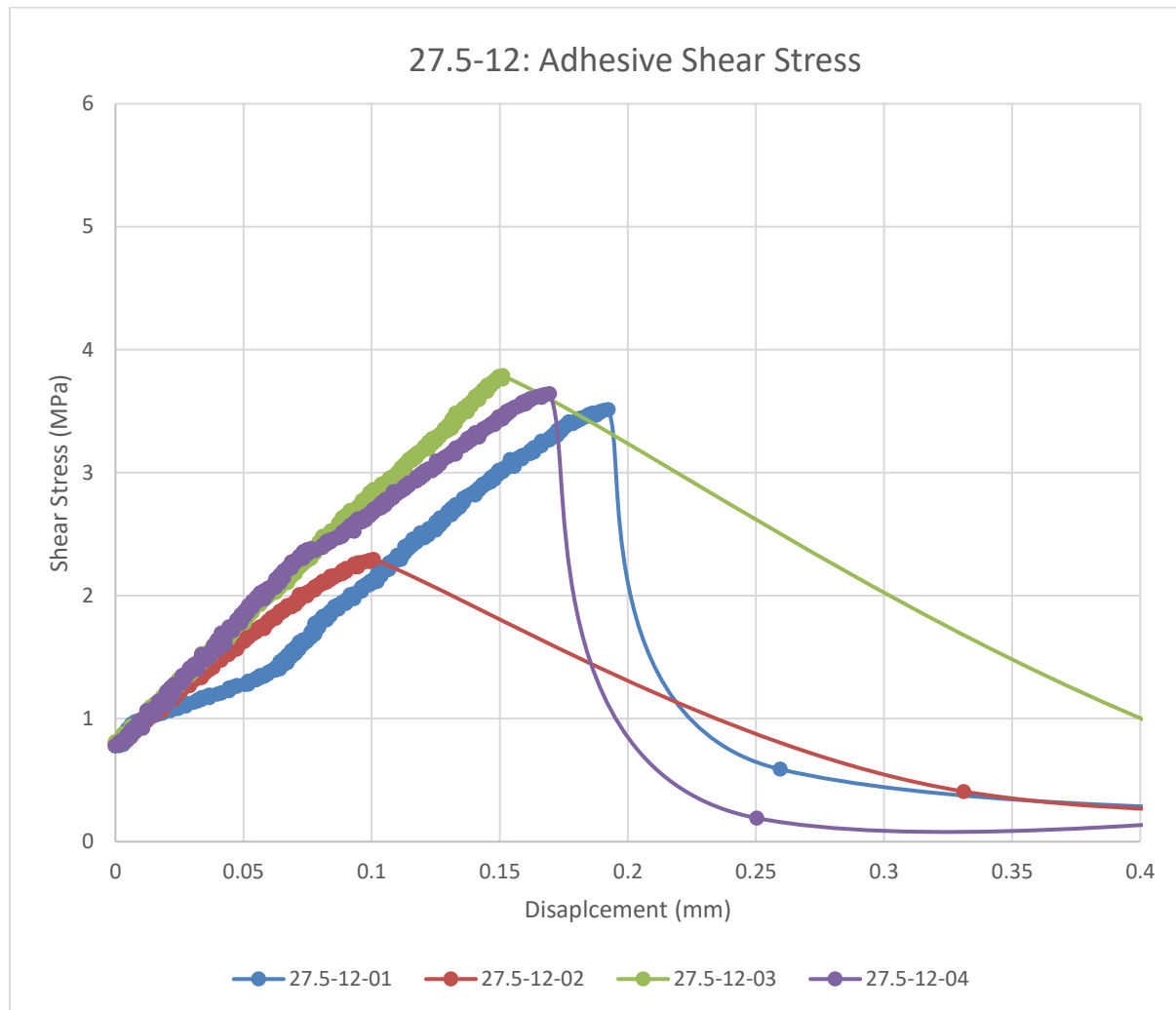


Figure A- 28 - 27.5-12: Adhesive Shear Stress

14.4 Shot Blasted and Vapour Blasted

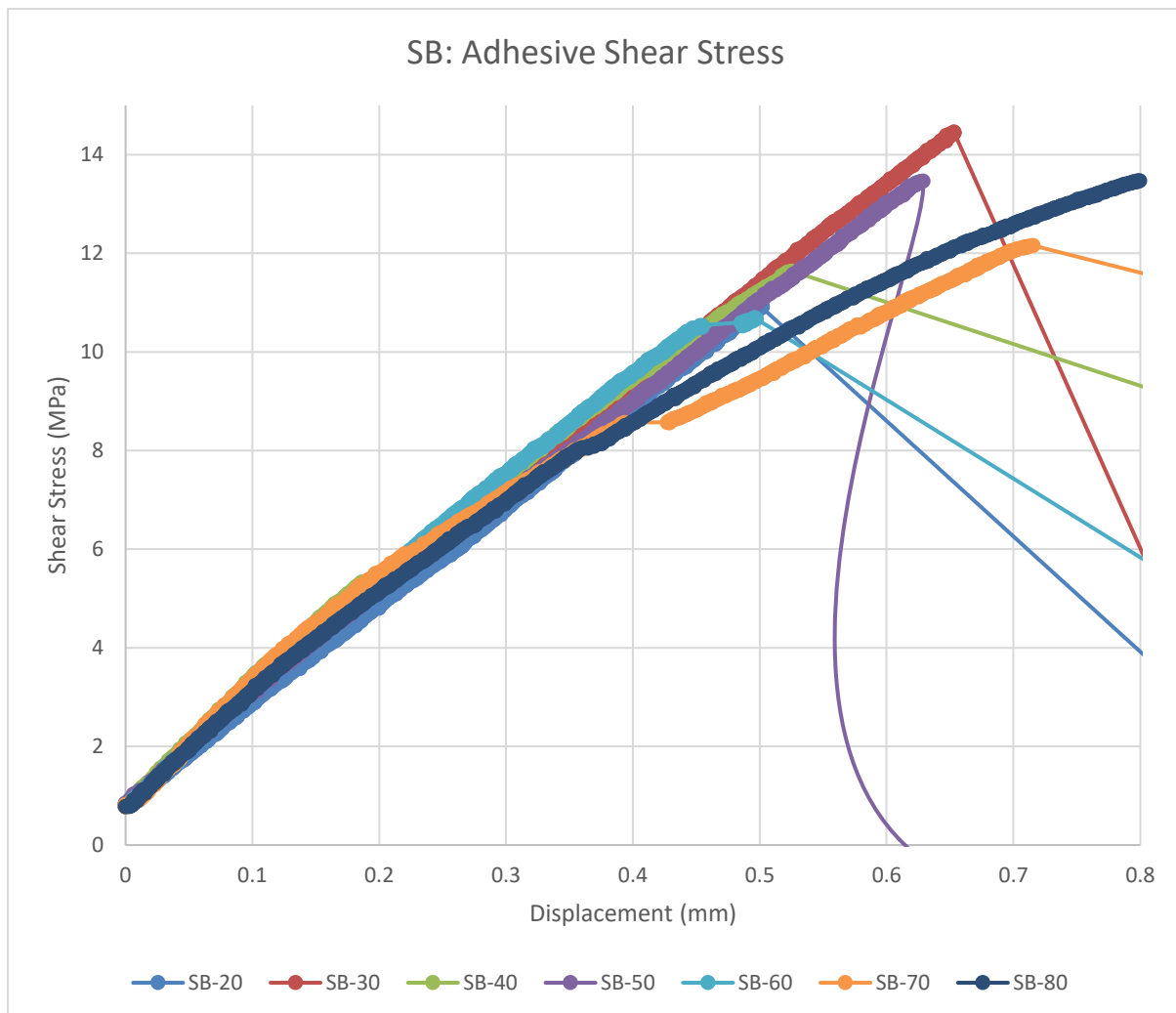


Figure A- 29 - SB: Adhesive Shear Stress

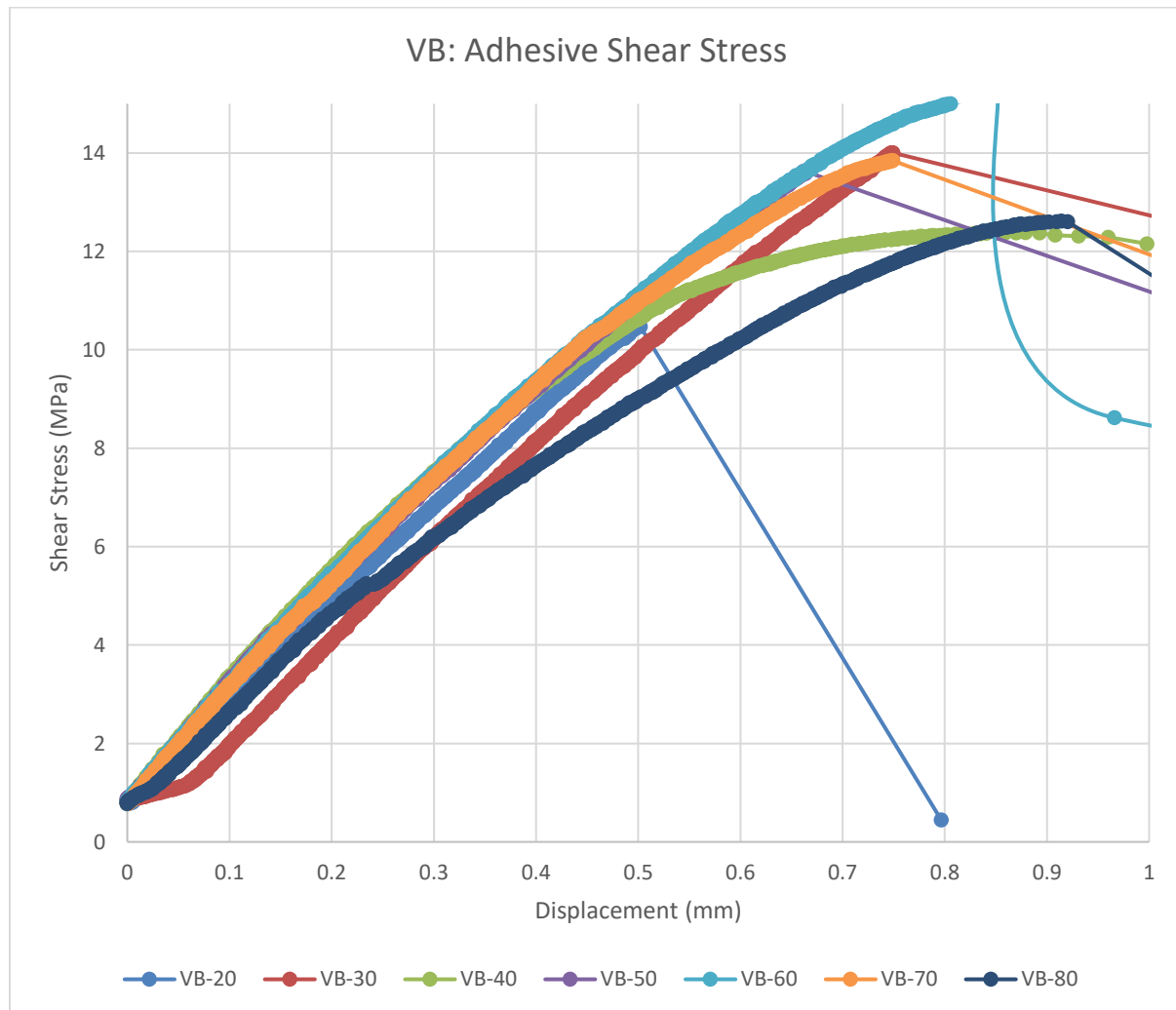


Figure A- 30 - VB: Adhesive Shear Stress

14.5 Bond Thickness Measurements

Name (Pairs)	CFRP	Thickness	Adhesive	Name (Pairs)	CFRP	Thickness	Adhesive
6_12_01	3.23	4.37	1.14	12_12_01	3.68	4.33	0.65
6_12_02	3.4	4.39	0.99	12_12_02	3.3	4.19	0.89
6_12_03	3.38	4.39	1.01	12_12_03	3.5	4.06	0.56
6_12_04	3.36	4.32	0.96	12_12_04	3.66	4.37	0.71
6_12_05			0	12_12_05			0
6_14_01		cut		12_14_01	3.42	4.18	0.76
6_14_02	3.25	4.22	0.97	12_14_02	3.29	4.29	1
6_14_03	3.43	4.38	0.95	12_14_03	3.36	4.37	1.01
6_14_04	3.66	4.36	0.7	12_14_04	3.33	4.34	1.01
6_14_05			0	12_14_05			0
6_17_01	3.75	4.5	0.75	12_17_01	3.81	4.58	0.77
6_17_02	3.32	4.32	1	12_17_02	3.35	4.33	0.98
6_17_03	3.43	4.59	1.16	12_17_03	3.36	4.36	1
6_17_04	3.42	4.37	0.95	12_17_04	3.33	4.34	1.01
6_17_05			0	12_17_05			0
6_17_01 *	3.31	4.34	1.03				
6_17_02 *	3.61	4.37	0.76				
6_17_03 *	3.37	4.35	0.98				
6_17_04 *	3.58	4.37	0.79				
6_17_05 *			0				

Name (Pairs)	CFRP	Thickness	Adhesive	Name (Pairs)	CFRP	Thickness	Adhesive
18_12_01	3.62	4.43	0.81	24_12_01	3.57	4.16	0.59
18_12_02	3.65	4.47	0.82	24_12_02	3.57	4.15	0.58
18_12_03	3.45	4.26	0.81	24_12_03	3.28	4.21	0.93
18_12_04	3.52	4.29	0.77	24_12_04	3.53	4.2	0.67
18_12_05			0	24_12_05			0
18_14_01	3.37	4.14	0.77	24_14_01	3.38	4.3	0.92
18_14_02	3.81	4.45	0.64	24_14_02	3.63	4.57	0.94
18_14_03	3.49	4.1	0.61	24_14_03	3.4	4.34	0.94
18_14_04	3.65	4.12	0.47	24_14_04	3.35	4.38	1.03
18_14_05			0	24_14_05			0
18_17_01	3.67	4.35	0.68	24_17_01	3.57	4.43	0.86
18_17_02	3.82	4.49	0.67	24_17_02	3.36	4.26	0.9
18_17_03	3.36	4.37	1.01	24_17_03	3.37	4.3	0.93
18_17_04	3.39	4.38	0.99	24_17_04	3.55	4.22	0.67
18_17_05			0	24_17_05			0



Name (Pairs)	CFRP	Thickness	Adhesive
27.5_12_01	3.64	4.37	0.73
27.5_12_02	3.35	4.38	1.03
27.5_12_03	3.57	4.3	0.73
27.5_12_04	3.37	4.28	0.91
27.5_12_05			0

Figure A- 31 – Bond Thicknesses