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Study on surface treatment for the Strength of bonded joints between CFRP Components

Master Thesis

**Course – MMTM05 Degree Project in
Production and Materials engineering**

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Abstract

Bonded joints is one of the most common connecting methods between components made from Carbon Fibre Reinforced Polymers, CFRP parts and especially in aviation applications. However, the strength of such bonds is largely affected by the surface preparation, where sanding being the most established but also a very time-consuming option. This thesis investigates the effect that surface preparation has on the single lap shear strength and peel strength of bonded joints between carbon fibre parts. In total three different surface preparations, (method A), (method B) and traditional surface preparation by sanding (BL) are compared for three different CFRP plies. The evaluation is made by comparing the measurement result for single lap SL tensile test and a modified double cantilever beam (MDCB) test. The thesis is performed in collaboration with Blackwing Sweden AB to see if the alternative methods for surface preparation could be suitable substitutions for traditional sanding.

The results show that the shear strength for specimens prepared with method A and B perform equal or better in the single lap shear compared to the traditional method of sanding BL. For peel strength however, method A and B looks to perform equal or slightly worse compared to sanding method BL. The obtained data for peel strength is however insufficient to draw a definitive conclusion and further peel test on corresponding layups as were tested for single lap shear need to be performed. The conclusion has subsequently bridged the gap between R&D and production by further providing information on structural adhesives in industry and its use with CFRP components.

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1. Introduction

1.1. Background

Since 2015 Blackwing Sweden AB is producing aircraft of type ultralight and has of today three models in production, -BW 600RG, BW 635RG, and BW650. All are two-seater aircraft with a 8.4 m wingspan and an empty weight of 335 – 375 kg [1]. Requirements for ultralight light aircraft vary depending on region but commonly for all that is a requirement for low weight [2]. To accommodate the low weight, while maintaining the strength and stiffness required, Blackwing manufacture their aircraft with a high contribution of parts made by Carbon Fibre Reinforced Polymers, CFRP.

To bond carbon fibre parts to one another, a common approach is to use different types of adhesives to create bonded joints. Benefits of this include the potential for stronger bonding per overlapping area and reduced stress concentrations compared to mechanical connections like bolts or rivets. It is also, in many applications, a simpler solution since the geometry of the bolt (or rivet) can be excluded from the design [3], [4]. This is also true for Blackwing where a substantial amount of glue is used to bond parts like the wing together. Surface treatment, by means of sanding, is often used to remove contaminants and epoxy matrix that could weaken the bonded joint. This also increase the surface area of the joint by generating tiny groves for the adhesive to get into. [5]

Sanding is however a time-consuming task that requires a lot of manhours. When the wings at Blackwing are to be glued. This is preceded by 4 hours of sanding and cleaning per wing before the glue can be applied. Therefore, Blackwing has been looking into alternative methods to prepare the surface to be glued, that would remove the need for sanding. Transition to using a new method, requires proof that the new joints meet the required shear and peel strength. This can be achieved by performing two different tests to evaluate on test samples subjected to preparation methods A, B, and Baseline BL, for a set of configurations.

1.2. Aim & Objective

Here the goal and desired outcome of the project is stated in *1.2.1 Contribution to company* and *1.2.2 Contribution to science*.

1.2.1. Contribution to company

Blackwing Sweden AB has of today performed test that indicates that a transition to the new method for bonded joints could be possible. The outcome of this thesis could provide evidence

that the bonded joint for such a new method is equivalent, or better than, bonded joints prepared with sanded surfaces. If proven reliable, the new method can be incorporated into Blackwing production. Thus, reducing production time and labouring cost compared to the aircraft produced today. The test in the thesis is performed in respect to current ISO standards. Thus, contributing to a higher validity of the result and added value to Blackwing Sweden AB.

1.2.2. Contribution to science

The topics of this thesis will cover adhesive bonds, CFRP and surface treatment. The results aim to determine how various surface preparation methods for bonded joint affects the shear and peel strength of the joint. Providing information on how adhesives in industry can be used in combination with CFRP components. Which, as a result would bridge the gap between R&D and production.

1.3. Research Questions

1. How is the shear- and peel- strength of the bonded joint related to surface preparation using Method A and Method B of CFRP components, respectively to the baseline Method BL.
2. Does the result indicate a feasibility to substituted Method BL for Method A and/or Method B.

1.4. Constrains

For the scope of this thesis, no further properties apart from the lap shear strength and peel strength for the bonded joints between CFRP will be investigated. Further, no other materials [than CFRP] will be investigated for the sake of this thesis. The thesis investigates the lap shear strength for three different methods for surface preparation. Method A, Method B and Method BL. The three different methods are evaluated on three different layups, one made by a 285 gram per square meter [gsm] Pre-Preg ply, a second with 600 gsm Pre-Preg ply, and a third made from Textreme [6], here named “Tx”. This is resulting in nine different configurations to be tested. Investigations of the peel strength are performed on the basis of the same three surface preparation methods but for only the 285-gsm layup.

2. Theoretical background

This chapter establishes this project technical framework. The framework utilizes established knowledge and applications to provide the reader with the necessary information to follow and comprehend this report.

2.1. Carbon fibre reinforced polymers

Carbon fibre reinforced polymers (CFRP) can be sorted under the umbrella of composites. Composites can be described as a material where two or more individual materials are combined to achieve overall improved material properties that cannot be met by either material separately. As for all composites, the material consists of a matrix material and a reinforcement. The purpose of the matrix is to keep the material in a continuous phase and maintain the reinforcements in the correct spacing and orientation relative to each other. The matrix also protects the reinforcement from abrasion [7]. In CFRP the matrix consists of some sort of epoxy resin that can be introduced to the fibres in various ways and stages of manufacturing [8]. As for the reinforcement in the CFRP is the carbon fibre itself. The reinforcement contributes to the material's overall strength and stiffness. Typically for carbon fibre, the reinforcements are manufactured into weaves. The epoxy is later, either pre-impregnated to the fibres before it can be used to manufacture parts, or it can be applied as liquid resin to the dry fibre during the part-manufacturing phase through either wet-layup or resin infusion. Method of choice is largely affected by factors such as time, cost, scale and precision [9].

Due to excellent characteristics of CFRP such as high strength to weight ratio, composites and CFRP have found an increase in application within the automotive sector as well as aviation and aerospace industry and more. In the automotive sector the motivation to utilise CFRP is weight reduction without compromising the safety of the driver. Thus, improving the energy efficiency. The low weight CFRP for energy efficiency is sought after also in aviation and aerospace industry. [8] With excellent thermal resistance also being a huge factor to its application there [8],[10].

Amongst composite materials, different failure mechanisms can usually be observed. These are commonly separated into matrix cracking, fibre fracture, delamination or fibre matrix interface failure [11]. The occurrence of fibre-matrix failure generally is a result of thermal loading and are too small to observe with a naked eye but can cause larger cracks. However, according to S.L. Ogin, P. Brøndsted, and J. Zangenberg "*provided there is good wetting between the matrix and the fibers, and no porosity is present it is rare for a good bond not to be formed*" [12]. Matrix cracking describes splitting of the matrix of the composite and one of the more serious failures, greatly affecting the properties of the material and leading to many other fatal failures like splitting of fibres and delamination. Matrix cracking is often parallel to fibres [13] and propagates from

free edges and can be the result of both thermal load, quasi static loads and fatigue. Delamination in this case refers to interlaminar layers de-bond from another before the fibre itself shears. A type of interlaminar peeling which then leads to early failure of the part and is almost always a result of matrix cracking [12]. As for fibre fractures, they occur due to localized stress concentration. Once other failure mechanisms are present, stress concentrations are more prone to build up and generate fibre fracture.

2.2. Bonded joints

Bonded joint is one of the most common methods for attaching CFRP components. Benefits include in many cases, more distributed loads and reduces stress concentrations compared to bolts and rivets. Even if stress concentrations do occur for bonded joints, in which they commonly can be found in the perimeter of the bond where they can contribute to micro cracks [14]. This makes bonded joints popular in many CFRP applications. To achieve sufficient bonding, surface preparation should always be performed. Where sanding is by far the most common procedure. The surface of the CFRP part should be rough and be free from any contamination [15]. The primary reason for this is to increase the surface energy (J/mm^2) of the bond. Which has been shown to be one primary factor to good adhesion.

Lately, the request for alternative preparation methods to sanding have been invested in the industry given that sanding is a time consuming and labour-intensive process that require the use of personal protective equipment (PPE) due to the safety risks associated to CFRP particles. Amongst these UV-laser and plasma treatment propose a promising option with lap shear strength in many cases improving compared to traditional sanding and looks to be “highly reproducible, automatable and environmental-friendly alternative” [16], [17].

When CFRP and adhesive is put under some type of load to the point of failure, there are a few ways in which this may occur. First, cohesive failure within the adhesive is more common for weaker adhesive or thicker bond lined where stress concentration can propagate and generate cracks. Next is cohesive failure within the CFRP and describes the matrix or fibre (often as a result of matrix cracking) fail [18]. This is often the result of too high loads exposed to the bond, like shear or peel loads. Thirdly, when the failure occurs between the adhesive and the CFRP, splitting no matrix or fibre is called adhesive or interfacial failure. This can most commonly be seen whenever poor adhesion is achieved. Either through contamination of the bond surface or incorrect curing for the adhesive [19]. Finally, mixed modes where two or more of earlier mentioned modes are present simultaneously. This is by far the most common failure mechanism for real world application with several factors affecting the bond. [20]

2.3. Testing methods

Following chapter covers the theoretical background for the test and ISO standards that contributes to the design of test carried out in this project.

2.3.1. Single lap shear

The single lap shear test is a tensile test designed to investigate the shea strength of bonds between rigid-to-rigid bodies. The established standard for said test ISO 4587_2004 “Adhesive lap-shear bond strength is determined by stressing a single-overlap joint between rigid adherends in shear by the application of a tensile force parallel to the bond area and to the major axis of the specimen”-. The ISO 4587_2004 is a testing procedure popularized by the ease of implementation and simple design [15], [21]. Making it the most implement specimen type in industry for comparative studies of bonded joints and adhesives, including manufacturing. Adding to the credibility of the use, due to a broader dataset for comparison. The Single lap joint does however showcase a higher degree of peeling forces compared to, for example perimeter compared to double lap shear. Which as a result could lead to premature failure. [21]

The standard states that two 100x25 mm specimen is to be glued together with an overlap of 12mm. Previous dimensions should have a tolerance of 0.25 mm with exceptions of the specimen thickness of 1.6mm with a tolerance of +/-0.1. Geometry and load case as seen in **Figure 1**.

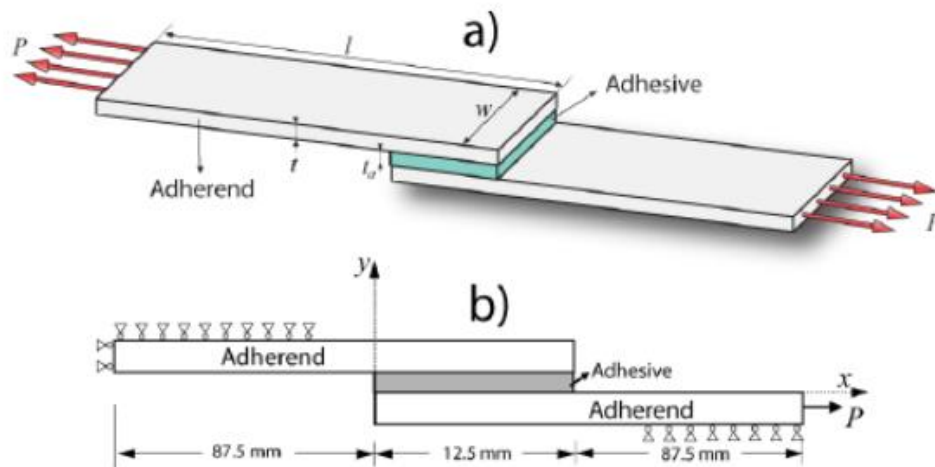


Figure 1 - a) Three dimensional single lap joint, b) Boundary conditions and geometric dimensions of bond joint.[22].

The test utilizes a tensile testing machine and results extracted are mean shear force in newton (N). As well as stress, in megapascals (MPa). The lap shear strength is calculated using $\sigma = \frac{F}{A}$ (1) Where σ is the

stresses inside the bond, F is the force applied force, parallel to the bond area and to the major axis of the specimen. A is the bond area in mm^2 .

It is to be noted that strength values obtained from this test should not be used as allowable design-stress values. To properly evaluate the results, a minimum of 5 samples should be tested be with the same conditioning. [6].

$$\sigma = \frac{F}{A} \quad (1)$$

2.3.2. Double cantilever beam

The double cantilever beam (DCB) is a test setup designed to determination the fracture resistance of structural adhesive joint. This while exposed to an applied crack opening load (mode I-). The standard DCB is thoroughly described in the ISO 25217:2009 [15] and expresses that two substrates should be bonded together and be equipped with either loading blocks or piano hinges in order to allow for the assembly to be exposed to the load case. To generate the required pre-crack, a non-stick film is to be inserted in between the two substrates from the end of the specimen to the crack initiation point. This makes up the distance a_0 as seen in **Figure 2**.

Dimensions in ISO 25217:2009 are non - specified but is rather selected based on the test that is to be performed. This test is either performed with loading blocks and pins, or piano hinged depending on what is most suitable for the application. If loading blocks is to be used. These sound be made out of aluminium alloy [22].

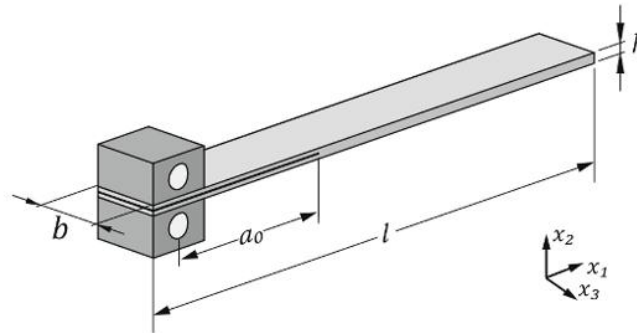


Figure 2 - Schematic view of DCB geometry [24]

2.3.3. T-peeling

The T-peel test is mentioned in the ISO 11339:2010 [24] is a tensile test that aims to determine the peeling strength of adherents by subjecting an adhesive a T-shaped bonded assembly of two flexible adherends bond to a peeling load as can be seen in The adherends should have a length of at least 200 mm to account for space to attach the grippers of the tensile-testing machine and a considerable distance to peel, along with a width of 25 mm with a tolerance of $\pm 0,5$ mm. The peel strength can be expressed as force per unit peel width [25]. From the test, the maximum,

minimum and average peeling force is captured over 100 mm out of a total of 150 mm bond, excluding an initial and final stint of 25 mm. Formulas for the peeling forces can therefore be formulated as (2) Where F can vary from F_{max} , F_{min} and F_{avg} . For $F = F_{avg}$ the calculation are formulated as in (3).

$$\frac{F}{l} \quad (2)$$

$$F_{avg} = \frac{1}{a-b} \int_a^b f(x) \quad (3)$$

Were a and b being the start and end points for your area of observation peeling, $f(x)$ is the force-displacement curve and F is the applied load in newtons N [24]. b is the width of the bonded specimen in (mm). From the test, the maximum, minimum and average peeling force in traced and measured over 100 mm out of a total of 150 mm bond. Excluding an initial and final stint of 25 mm. [24] This is to remove any deflection from the setup from As mentioned by Nick, Nick, and Wortmann (2000), “Due to this procedure large variations of strength caused by irregularities of the force data directly after the incipient crack at F_{max} and near the final failure of the specimen are eliminated.” [26]

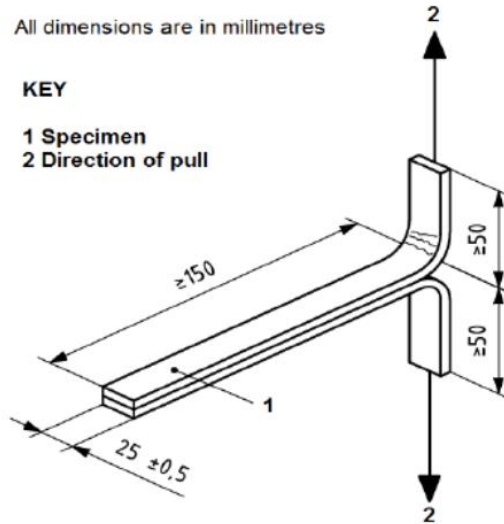


Figure 3 – Dimensions and load application for T-peel specimen [28].

3. Methods

This chapter cover the workflow of the project in terms of preparation, sample manufacturing, test procedure of the two different test specimens as well as additional tasks that are carried out.

3.1. Design of testing method

This section covers the reasoning behind the design, dimensioning and setup of the individual tests.

3.1.1. Single lap shear

As previously mentioned in 2.3.1, the single lap shear test is a common and well-established tensile testing procedure. Making it a credible option to use. The load case is also one that can be found in The dimensioning of the SL specimens follows that of ISO 4587:2004 [29], two specimens with the dimensions of 25x100x1.6 mm are glued together with an overlap of 12.5 mm. For all dimensions a deviation of ± 0.25 mm is considered acceptable for the standards. The thickness of the specimen according to ISO 4587:2004 should be 1.6mm $\pm$ 0.1 mm. With the expected cured thickness of 0.33 per ply. A stacking sequence of [0/90/0/90/0] is selected to reach the required thickness for the 285-gsm stack and get a more homogenous piece. For the 600 gsm with a theoretical cured thickness of 0.60 mm to achieve a thickness greater than 1.6mm. A stack of 3 are stacked up like [0/90/0] resulting in a theoretical thickness of 1.8mm. For the Textreme layup, to surpass the 1.6mm thickness, one layer of Textreme is added to the 600-gsm stack as [0/90/0/Tx] Specimens are prepared as a larger sheet and is then cut up into individual pieces according to the technical drawings seen in *Appendix A a)*.

3.1.2. Modified double cantilever beam

The modified double cantilever beam MDCB follows a similar setup to that of a traditional DCB as can be seen in ISO 25217:2011 [30]. For this project however, the objective is not to investigate the crack propagation or strain energy release rate G_I . The objective focuses instead of the peeling strength of the bonds. A trait that is commonly investigate between flexible-to flexible parts as specified in ISO 11339:20110 [25]. The two standards are therefore combined into a modified double cantilever beam that utilizes the setup of a DCB as specifies in [30] with loading block and two rigid bodies glued to each other. With the exemption that a pre-cracking is not generated through the introduction of the thin non-stick film. Instead, the bond is controlled to start 50 mm from the point of applies load to instead generate a peeling force. The information extracted from the test emulates that of 11339:20110, including the average and max peeling strength [25]. This approach has also been used by others in academic research such as A. Nick, B. Nick, F.-J. Wortmann. [27] Therefore the same geometry is used for the specimens in this

report as well as approach to force extraction of F_{max} and F_m and boundary intervals as seen in **Figure 4**.

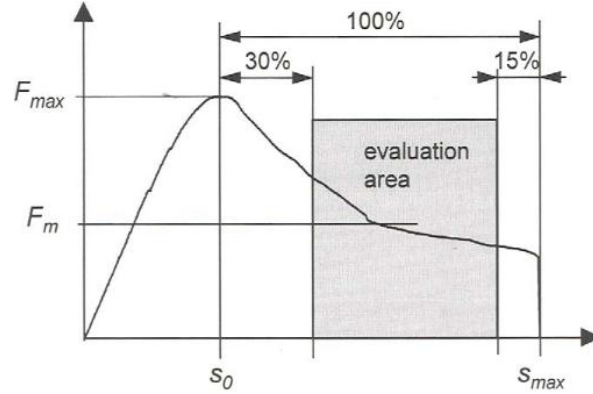


Figure 4 - Typical force/distance profile monitored during a peel test and illustration of the data evaluation from a force/distance profile of CFRP test specimen. [27]

The layup for MDCB specimen is the same as for SL specimen and are specified in 3.1.1. They are prepared as a larger sheet and is then cut up into individual pieces according to the technical drawings seen in *Appendix A b*). Loading blocks are cut out to the dimensions displayed in *Appendix A c*) from an aluminium rod and are glued to the top and bottom of the specimen. It is important that a low friction is kept between blocks and pin. This can be achieved with smearing and precision machining [31].

3.2. FEM

A finite element method approach is taken to observe stress distribution over the specimens. As well as looking at expected behaviour of the samples. The SL and MDCB specimens are modelled as laminates using the composite tool in Altair, HyperWorks to the geometry specified in 3.1.1 and 3.1.2. The adhesive for both tests is modeled with solid elements and are connected to the laminate substrate. The collection of parts is assembled and connected after which the load case is applied with associated material properties. The simulations are modelled with respect to the 285 gsm specimens in both the SL and MDCB case, since necessary material data for that specific CFRP was accessible to the project thanks to prior testing.

For the SL a distributed load over one edge is collectively 60 kN, while the other end is locked in all degrees of freedom. For the MDCB, a collective fore of 70 N is applied in the centre of one of the loading blocks, normal to the face of the bond. The other loading block have a boundary condition applied to the centre of it. Constraining it in all degrees of freedom with the exception

for rotation around the blocks centre axis. NOTE: Altair authorized the use of their license and software for use in this master's thesis.

3.3. Materials

Following materials and tools are used to execute this thesis.

Prepreg:

- A 285gsm 4x4 twill 42%RW
- A 600gsm 2x2 twill 38%RW
- A 160gsm spread toe plain weave, Textreme

Surface preparation materials (Peel ply):

- Type A 50%RW
- Type B

Adhesive:

- Huntsman structural adhesive (Araldite 2019)

Measuring:

- Universal testing machine
 - Loading capacity: 25kN
- Extensometer
 - Precision of 1×10^{-4} mm
- Calliper
 - Precision of 5×10^{-2} mm
- Micrometre
 - Precision of 1×10^{-2} mm

Other:

- Aluminium 6082-T6 (Used for MDCB loading blocks)
- Stainless steel (Used for MDCB loading pins)

3.3.1. Naming and Layup

Naming of the specified samples follows a system corresponding to test type, layup and surface preparations. The first 2-3 letter combinations indicate the type of test set-up, either single-lap SL or Modified double cantilever beam MDCB. This is then followed by one of three number/letter combinations T285, T600 or Tx. Indicating what layup is used for the sample. T285 indicates that the 285gsm twill is used. The in a sequence of [0/90/0/90/0]. For the T600 a 600gsm twill is used in a stack of [0/90/0]. Tx indicates that the spread-toe plain weave (commonly referred to as Textreme) is applied on top of the T600 stack. As an example, specimen SL_T600_BL_1 indicate that the specimen is one out of 5 specimens to be tested for the single lap (SL) test with a baseline (BL) preparation on the 600gsm layup.

3.4. Surface preparation

For this thesis, three methods, Method BL, Method A and Method B of surface preparation are evaluated for their relative lap shear strength and peel strength. The BL method refers to the baseline method of sanding the specimen prior to application of the adhesive. For this project the surface to be bonded is thoroughly sanded using a random orbital sander with an 80-grit paper by an Blackwing operator. The surface is then cleaned using acetone to remove any contaminating particles. This is done once the specimens have been cured in the autoclave and just before the adhesive is applied.

Surface preparation A refers to applying of the type A peel-ply on the A-side of the specimen (between specimen and glass sheet). This type of peel-ply is, in collaboration with the supplier, pre-impregnated to effectively be applied to the mould surface without wrinkling. This is not an issue for the sake of this project but would be in other applications. Therefore, the pre-impregnated peel-ply needs to be evaluated. The peel-ply is applied as the first layer during the layup phase of manufacturing the specimen before bagging the pieces for the autoclave.

For surface preparation B, a more traditional peel-ply (non-pre-impregnated) is used for the B side on the specimen (between specimen and bag). This peel-ply just as for Method A is applied to the specimen during the layup stage before bagging

3.5. Sample Preparation

This segment describes all essential steps, carried out to manufacture both types of test specimens. Both samples, SL and MDCB types are prepared at Blackwing facilities in collaboration with operators on sight to achieve good manufacturing practice and not deviate from the manufacturing procedures commonly used by the personnel. Additional tasks are carried out at the institution of industrial production and solid mechanics at LTH. As well as Lunds Öppna Verkstad (LÖV).

In total, to account for 5 samples plus two spare ones for each combination of layup and surface preparation. A total of 63 SL assemblies and 21 MDCB assemblies including 42 loading blocks are manufactured for this thesis.

3.5.1. Safety

Throughout the duration of this project, precaution such as, use of proper protective equipment has been put in place to maintain the safety of the people involved. This includes the use of nitrile gloves and long-sleeved shirts whenever operating with uncured carbon fibre or adhesive. Protective overalls and 3P or equivalent particle filters for breathing are also used whenever cutting or sanding carbon fibre is carried out.

3.5.2. Layup

For both the SL – and the MDCB manufacturing of the specimens follows similar procedures. The prepreg CFRP for the specimens is cut in larger sheets to allow for several pieces to later be cut out from one assembly. The prepreg CRFP is cut out from a roll using a cutting machine as can be seen in **Figure 5**. The machines are fed the dimensions of the sheets from dxf-files and is then cut out for the desired number of plies in the 0 ° and 90 ° directions. This procedure makes sure that the desired dimensions of the plies are obtained as well as maintaining the dimensions consistently between each layer.

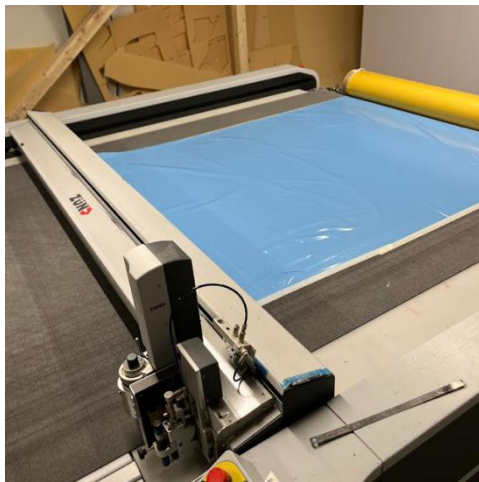


Figure 5- Procedure of cutting the CFRP to desired dimensions.

The subsequent step combines the individual plies into a laminate. The plies are stacked on top of each other on a glass sheet prepared with acetone and release agent. Since two laminates (top and bottom) are combined to make one test specimen. For each layup and preparation combination, two laminates are combined. Here the additional preparation method is applied. Nothing extra is added in terms of the (BL) specimen. For method A and B, two separate additional tasks are performed to those type of specimens for each layup. For SL specimens, combining layup variants (3st), with types of surface preparations For The glass sheet is the

bagged with standard procedure using release film, breather and bag. The layups are grouped so that parts that are to be assembled, lay together and are marked with layup and surface preparation as can be seen in **Figure 6**.

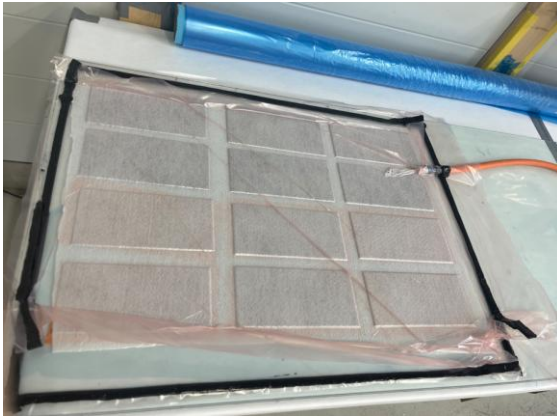


Figure 6 – Bagging and grouping of test specimen.

When the larger sheets of specimen have been bagged, they proceed to the autoclave to be cured. All specimens are cured at 5 bars pressure. The temperature is first ramped up for a duration of 2 hours up to 120 °C. This temperature is thereafter maintained for a duration of 5 additional hours.

3.5.3. Application of adhesive

Once fully cured the specimen are de-bagged and prepared to be glued together. First, the specimen labelled BL are sanded thoroughly using 80 grit paper by the operator at BW and is then cleaned using acetone and paper towels. For the A and B specimens, these are already considered prepared following the curing and no further procedure is therefore taken before these can be glued.

For SL assembly's, a release-tape is used to mark out the 12,5 mm overlap on the individual pieces as displayed in **Figure 7 a)**. This is to protect the glue from spreading beyond the desired area and to work as masking tape and more effectively clean the edge of the bond. The glue can then be added to the specimen using a pneumatic gun and nozzle. The assembly is rigged up using wooden sticks to align the samples and to evenly distribute the loads from the clamps as can be seen in **Figure 8 a)**. A decent string of adhesive is applied over the desired surface and is then distributed from pushing the specimen together. Allowing for bonding over the entire desired surface. Edges are cleaned using the same wooden sticks as for clamping and aligning. For places where bonds are expected to not form.



Figure 7 - Preparation of cured pieces of a) - SL and b) – MDCB.

For the DCB samples, the same procedure is taken to bond the pieces together. But with the difference that the assembly is pressed down using wooden blocks to evenly distribute the pressure over the entire bonding area displayed in **Figure 8 b)**. Another difference is that the application is done using a brush. This is to better control an even layer over the entire surface. Making sure the adhesive doesn't spread to the area that is going to be non-bonded (a0). To further hinder the adhesive to enter the a0 area, a stack of 4 layers of 0,05 mm release tape is stacked on top of each other (corresponding to the predicted bond thickness) to form a protective wall, separating the adhesive from the non-bonded area. As can be seen in **Figure 7 b)**. After application, adhesive is applied and is to undergo a primary curing in ambient temperature overnight which correspond to the usual production procedure for Blackwing. Once the primary curing is performed a secondary curing is performed in oven, rising the temperature linearly for 30 min up to 60°C where it is kept for an additional 30 min. This is followed by rising the temperature for 250 min until 110 °C where it is maintained for 180 min.

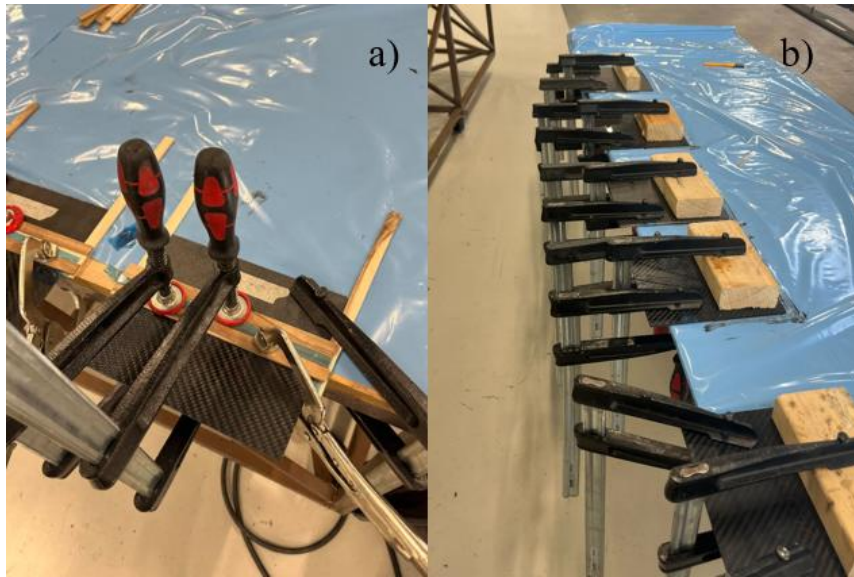


Figure 8 - Clamping of test pieces after glue application for a) SL - assembly and b) MDCB - assembly

3.5.4. Cutting

Once all specimen types are glued together. All specimens undergo a cutting process off splitting each specimen assembly up into a set of seven substrates. Accounting for the required five test from the iso standards [29],[30],[25] as well as two spare substrates in case of any unforeseen errors or mistakes during testing. Cutting is performed accordingly with *Appendix A* and *Appendix B*. The splitting action took place at the three different locations based on availability since time was a limiting factor. Cutting of the pieces are performed at institution of industrial production, the institution of solid mechanics at LTH. As well as Lunds Öppna Verkstad (LÖV) as seen in **Figure 9** below.

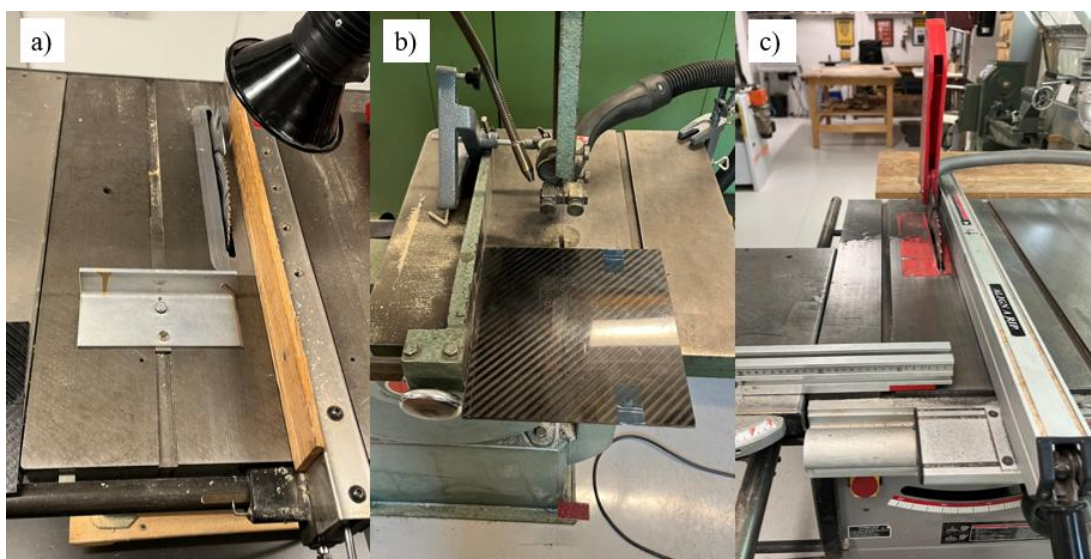


Figure 9 - Table saw at institution of solid mechanics a), Band saw at institution of production and materials b), Table saw at LÖV c).

3.5.5. Additional Tasks

To execute the tests. Some additional task is required. These include additional grinding on a belt sander to some specimen where the cutting process resulted in to rough or uneven cuts. Finally, all SL pieces are sanded and cleaned on the surface that go into the gripper of the UTM. This is to roughen up the surface to try and avoid slipping between the specimen and the grippers. Additional task also includes manufacturing of loading blocks for the MDCB. The blocks are cut from a 20x20 mm, 2 m rod in intervals of 25 mm to match the width of the specimens. See *Appendix A c*). The blocks are face milled to get a clean edge that are later use to line up with the specimen sides. After milling, a through-hole of 6 mm is drilled through each block to accommodate the 6mm stainless steel rod. This process is repeated 42 times so that each specimen per preparation method could be fitted with two blocks each. The blocks along with the MDCB specimens are sanded on connecting sides and are then cleaned with acetone to allow for proper adhesion between the block and substrates. Once cleaned the blocks and substrates are glued and clamped as shown in **Figure 10**. Protective plastic is also inserted in between the substrates to protect them from getting glued together. Throughout the manufacturing phase whenever the pieces are not processed, they are kept in a plastic box, wrapped in breather material to protect them from grease, liquids or other physical impact in any form that might affect the bond performance.



Figure 10 - Clamping of MDCB assembly post application of adhesive

Before all tests being performed, the geometry for both SL and MDCB specimens is individually measured to see how well tolerances have been met. This is performed using analogue calliper and micrometre. The result of these measurements can be found throughout chapter 4.

3.6. Experimental tests

Following chapters covers critical information regarding the how the SL and MDCB test are performed. This includes set-up, how the test is performed and what data that are extracted from the tests. To preserve one of each sample types for additional test at Blackwing. From the 63 SL specimen and 21 MDCB specimens that are manufactured. A total of 54 SL tensile test, and 18 MDCL peel test are performed.

3.6.1. Shearing – Single lap bond

The test samples are clamped parallel to the bond area and the major axis of the specimen. The specimen is clamped in between the self-aligning grippers in the universal testing machine to evenly distribute the load 50 mm from the bond line as seen in **Figure 11 a)**. A force is then applied in the same direction from one end at 10 mm/min while the other end is fixed to the base. To adjust for the slip between the specimen and the self-aligning grippers, for an additional set-up is manufactured. This consist of two 5mm steel plates bolted together using two M6 8,8 bolts. The specimen intersects the two plates and is clamped with both bolts symmetrically tightened to 10Nm using a ratchet wrench. The setup is displayed in **Figure 11 b)**. A displacement is attached to the upper clamp.

Captured data from each test is the momentary force for each sampling interval. As well as the displacement from the gauge. From this, force can be plotted against displacement and the ultimate lap shear strength can be extracted. The result can be seen in chapter 4.

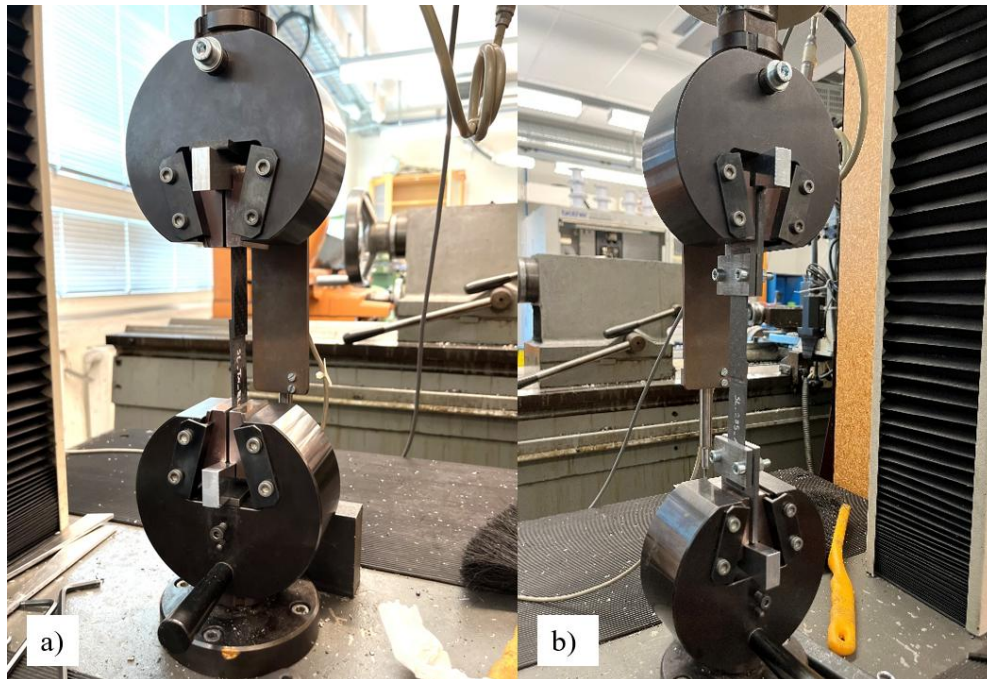


Figure 11 - Experimental set-up of Single Lap tensile with self-aligning grippers a) and with additional module b).

3.6.2. Peeling – Modified double cantilever beam

For this test, the self-aligning grippers are removed and replaced by steel modules with cut-outs for loading blocks and loading pins as seen in **Figure 12**. The cut-out allows for holding of the loading pin, as well as allow for the loading block to move freely around the pin axis. The pins are greased up as a part of the setup to reduce friction in the system. For the test, a force is applied normal to the bonding area at a constant crosshead rate of 15mm/min. The force is applied until the two bonded substrates are completely separated. For this test the gauge is also changed to one with a larger measuring span to account for the increased distance that the machine needs to travel in order to peel the substrates apart as can be seen in Before force is applied, the initial separation δ between the substrates are measured using a feeler gauge. This is then adjusted for in the plot to more accurately trace the displacement.

Just as for the SL tests, the extracted data is force N and displacement mm. From the data, force/displacement curves can be generated and max, min and mean peel strength be extracted according to the specifications mentioned in 3.1.2.

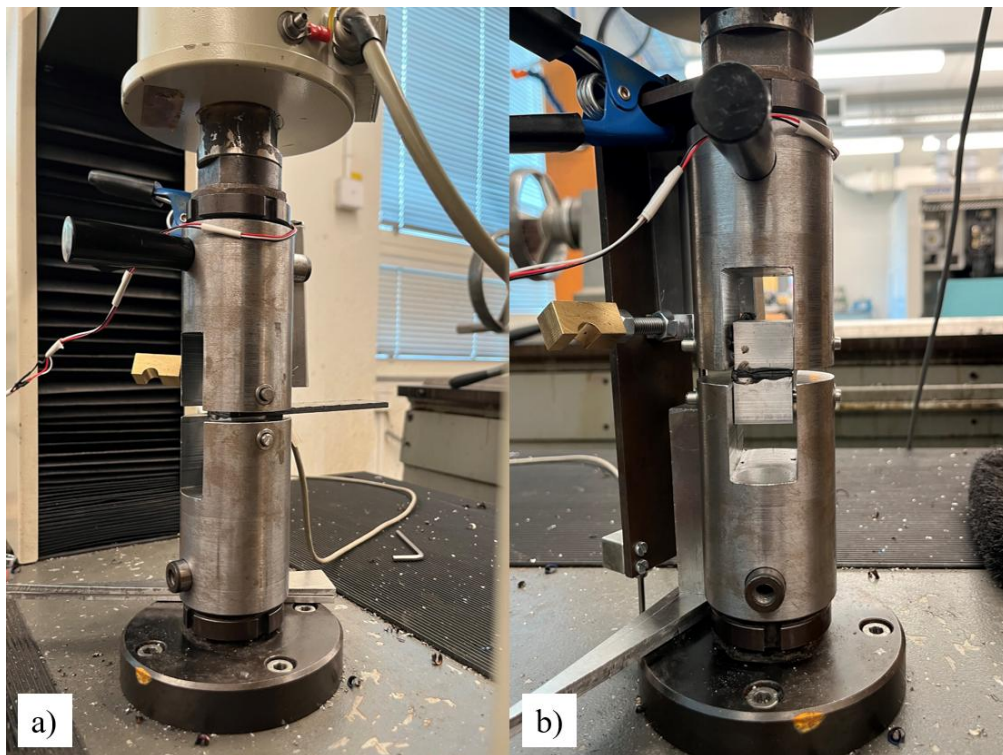


Figure 12 - Experimental set-up of MDCB peel test. Including steel module, loading blocks from a) sideview, and b) forward possession.

4. Results

This chapter displays the extracted data from the single lap tensile test and modified double cantilever beam covered earlier in the report. Diagrams and plots displayed in this chapter are generated through MATLAB with scripts that can be found in **Appendix B** – MATLAB code for plotting of data.

4.1. FEM Results

In **Figure 13** von Mises stress distribution is shown for a corresponding load of 60 kN under the SL scenario. Stress concentrations are observed around the perimeter of the bond, with peak of stresses at the corners of the adhesive joint. Here the simulated max stress is recorded at 965, N/mm^2 . For the MDCB simulations, von Mises stress distribution are concentrated at the peel propagation point of the bond. The results show a value of are 55,2 N/mm^2 from the applied force of 70 N.

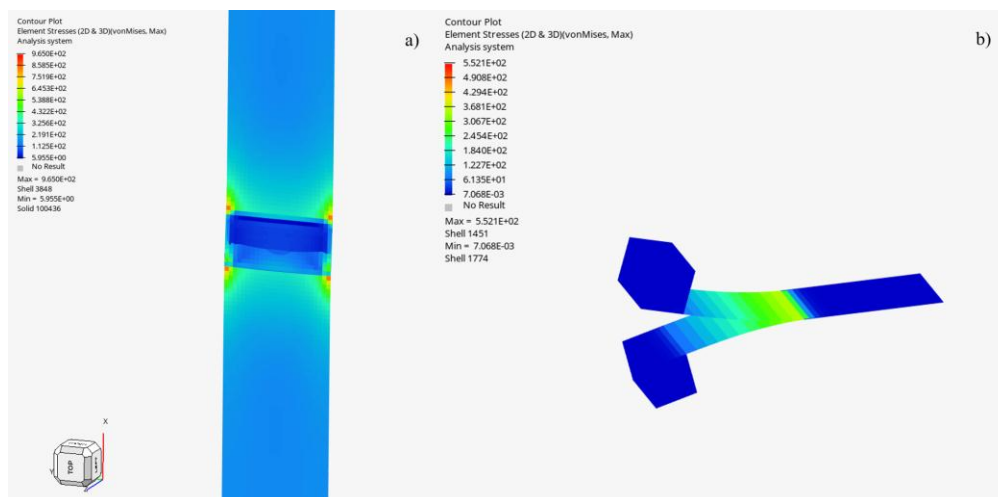


Figure 13 - Von Misses stress distribution for a) SL 285 specimen, and b) MDCB 285 specimen applying a Finite Element method.

4.2. Shearing – Single lap bond

Here, the force is compared to the elongation for the three different layups and respective three surface preparation for the single lap tensile tests. For all tests the shear force is recorded along with the deviation for each sample group.

4.2.1. SL 285 - Plots

From **Figure 14 a)-c)**, the shear force (N) of the individual single lap specimen of the 285-gsm layup is plotted against its corresponding displacement (mm) for all groups of preparation. These are all compared in **Figure 14 d)** based on max, min and mean shear force.

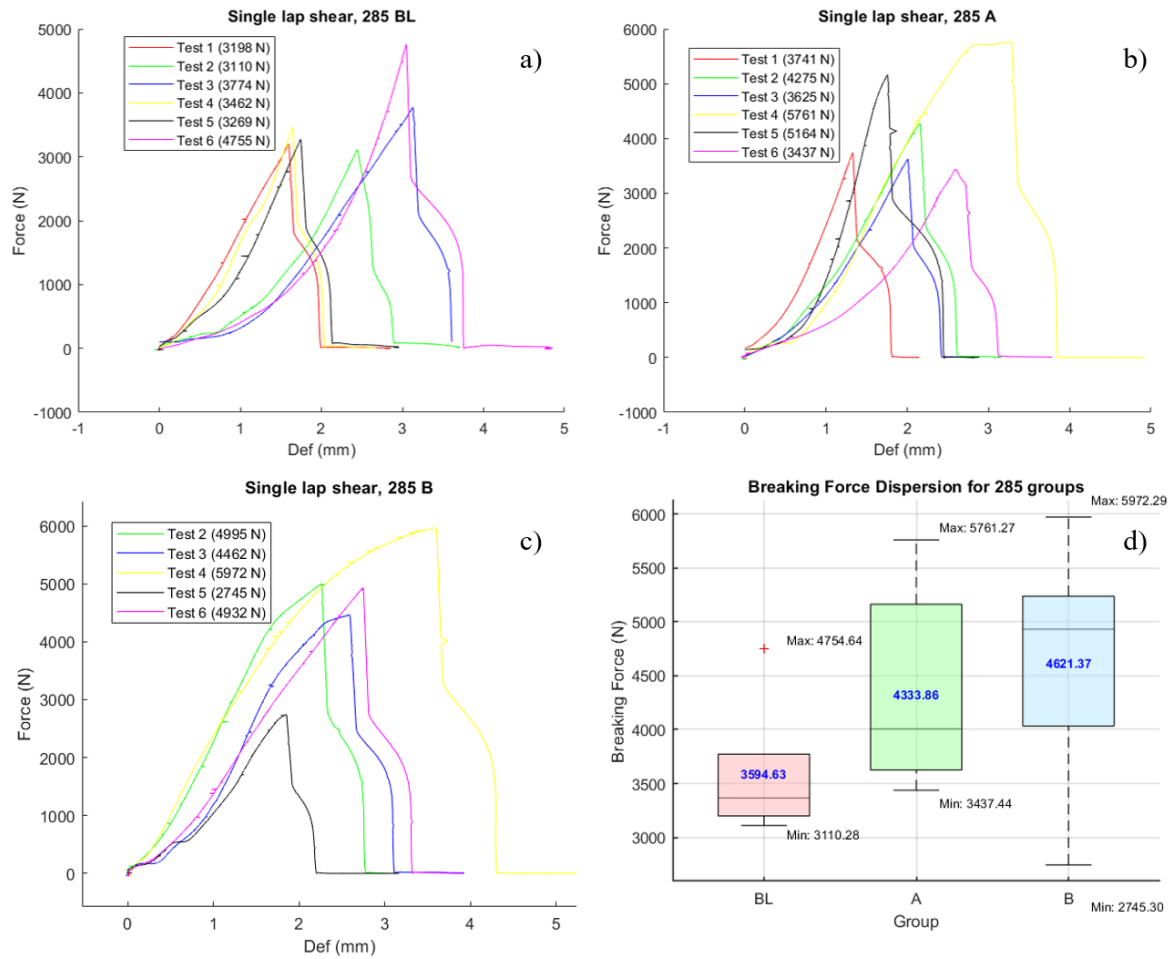


Figure 14 - Force/Displacement plot for SL 285 BL specimen a), A specimen b), B specimen c), Box diagram showing dispersion for all 285 tests d).

4.2.2. SL 285 – Fracture surfaces and Dimensions

Dimensions for all SL 285 specimen as seen in **Table 1**. Measured dimensions are a mean thickness of the assembly $2h$. One substrate thickness h . After which bond thickness h_b can be calculated. Measured is also width w , and overlap Ol and length l . Further, fracture surfaces for 285 group post tensile testing is shown in **Figure 15-17** below. Showcasing the different failure mechanism that are present for the earlier mentioned group.



Figure 15 – Fracture surfaces for a) - SL_285_BL group. And b) -Up close fracture surface for one SL_285_A sample.

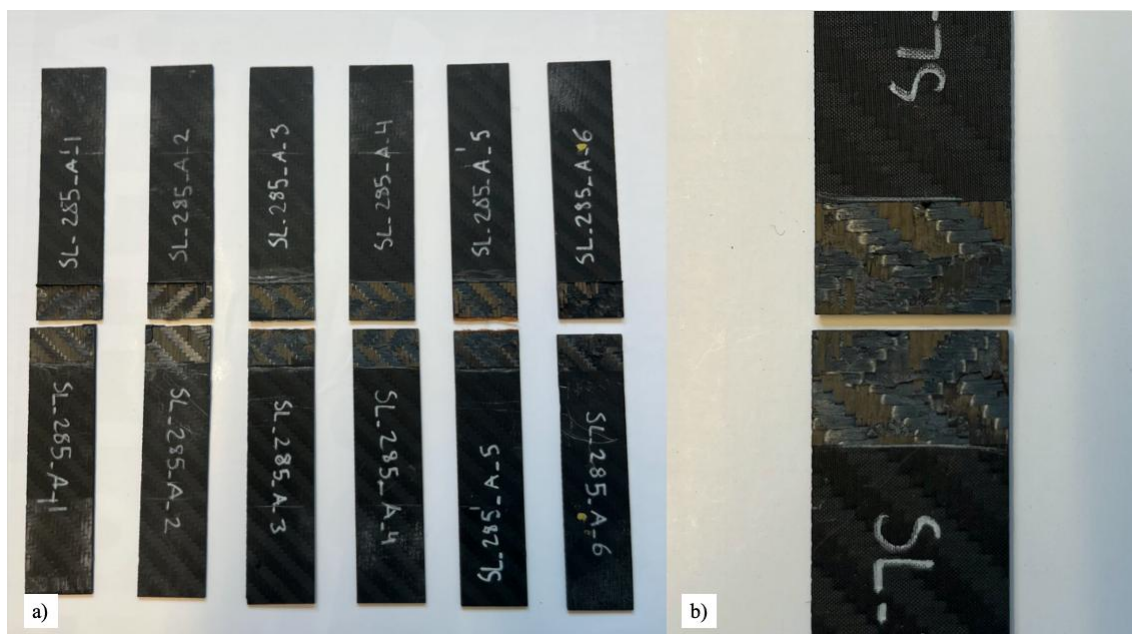


Figure 16 - Fracture surfaces for a) - SL_285_A group. And b) -Up close bonded surface for one SL_285_A sample.

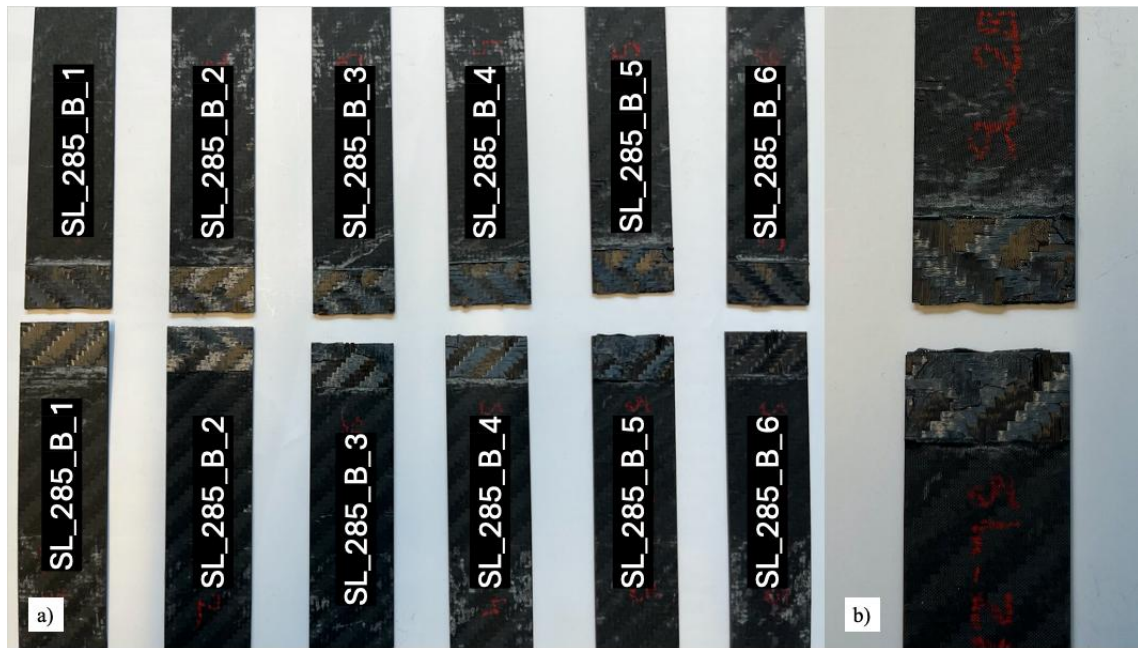


Figure 17 – Fracture surfaces for a) - SL_285_B group. And b) -Up close bonded surface for one SL_285_B sample.

Table 1 – Measured dimensions for SL specimen in the 285 group.

SL	H (mm)	h (mm)	Ol (mm)	b (mm)	A (mm ²)	l (mm)	bond (mm)	Done	Max (N)	(Mpa)	Note
285_BL_1	3,16	1,49	12,95	25,2	326,34	100	0,18	☒	3198	9,799595514	
285_BL_2	3,3	1,53	13	25	325	99,15	0,24	☒	3110	9,569230769	
285_BL_3	3,2	1,53	13,25	24,95	330,5875	99,75	0,14	☒	3774	11,41603963	
285_BL_4	3,2	1,53	13,2	25,15	331,98	100,35	0,14	☒	3462	10,42833906	
285_BL_5	3,3	1,5	13,15	25,1	330,065	100,1	0,3	☒	3269	9,904109797	
285_BL_6	3,15	1,54	13,14	25,2	331,128	100,25	0,07	☒	4755	14,3600058	
285_BL_7								☐			
mean	3,218333	1,52	13,115	25,1	329,1834	99,93333	0,178333		3594,667	10,91288676	
285_A_1	3,3	1,62	13,8	24,95	344,31	99	0,06	☒	3741	10,86520868	
285_A_2	3,47	1,6	13,6	24,7	335,92	99,2	0,27	☒	4275	12,72624434	
285_A_3	3,26	1,58	14,5	25	362,5	99,5	0,1	☒	3625	10,86520868	10 peal ply left ?
285_A_4	3,32	1,6	13,5	24,85	335,475	99,5	0,12	☒	5761	17,17266562	
285_A_5	3,29	1,6	12,26	24	294,24	99,1	0,09	☒	5164	17,55029908	
285_A_6	3,5	1,61	13,85	23,95	331,7075	98,8	0,28	☒	3437	10,3615384	
285_A_7								☐			
mean	3,356667	1,601667	13,585	24,575	334,0254	99,18333	0,153333		4333,833	13,11265935	
285_B_1	2,92	1,43	12,7	25,2	320,04	99,5	0,06	☒			no data
285_B_2	2,84	1,39	13	25,2	327,6	100,15	0,06	☒	4995	15,24725275	
285_B_3	3,16	1,44	12,8	25	320	100,2	0,28	☒	4465	13,953125	
285_B_4	2,93	1,43	12,7	25,2	320,04	100	0,07	☒	5927	18,51956005	
285_B_5	2,95	1,42	13	25,2	327,6	99,9	0,11	☒	2745	8,379120879	
285_B_6	2,95	1,44	12,85	25,25	324,4625	100,1	0,07	☒	4932	15,20052394	
285_B_7								☐			
mean	2,958333	1,425	12,84167	25,175	323,2904	99,975	0,108333		4612,8	14,25991652	

4.2.3. SL 600 - Plots

Figure 18 a)-c), showcases the shear forces (N) for the individual single lap specimen of the 600-gsm layup. These are plotted against its corresponding displacement (mm) for all groups of preparation. The test is all compared in **Figure 18 d)**, based on max, min and mean shear force.

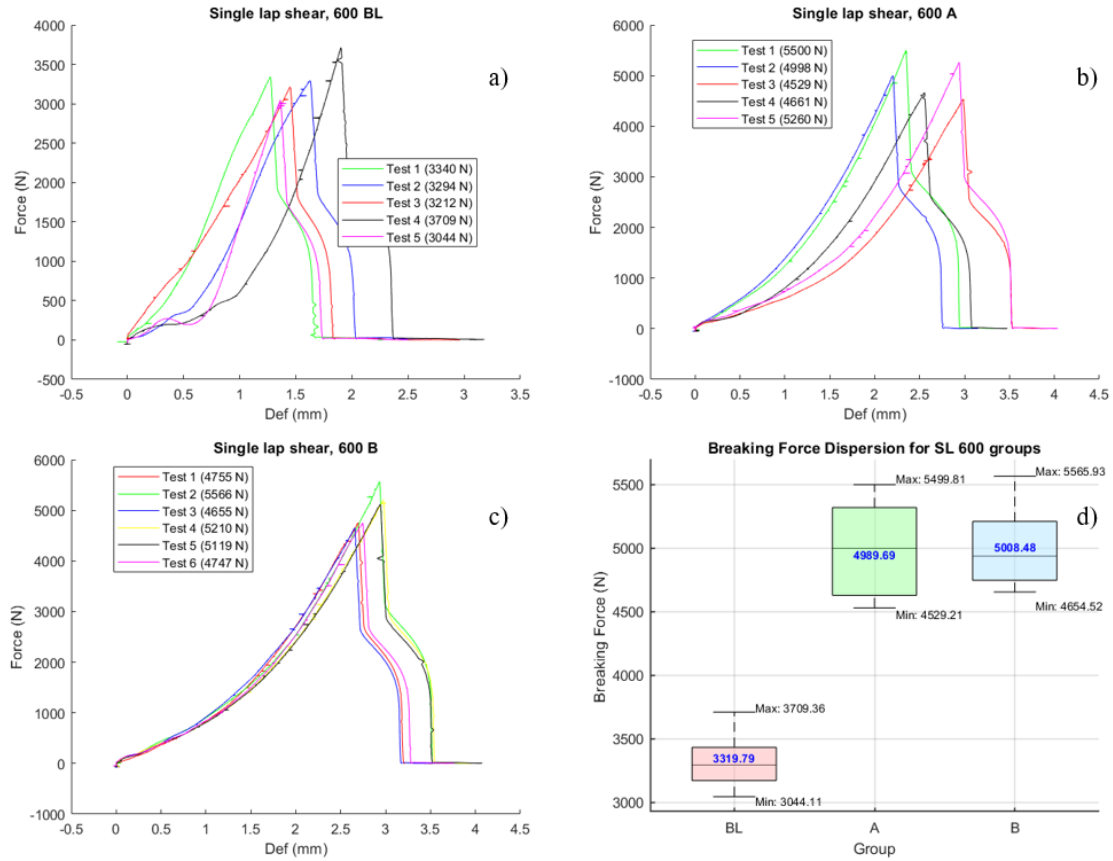


Figure 18- Force/Displacement plot for SL 600 BL specimen a), A specimen b), B specimen c), Box diagram showing dispersion for all 600 tests d).

4.2.4. SL 600 – Fracture surfaces and dimensions

Dimensions for all SL 600 specimen as seen in **Table 2**. Measured dimensions are a mean thickness of the assembly $2h$. One substrate thickness h . After which bond thickness h_b can be calculated. Measured is also width w , overlap Ol and length l . Further, fracture surfaces for Tx group post tensile testing is shown in **Figure 19-21** below. Showcasing the different failure mechanism that are present for the earlier mentioned group.

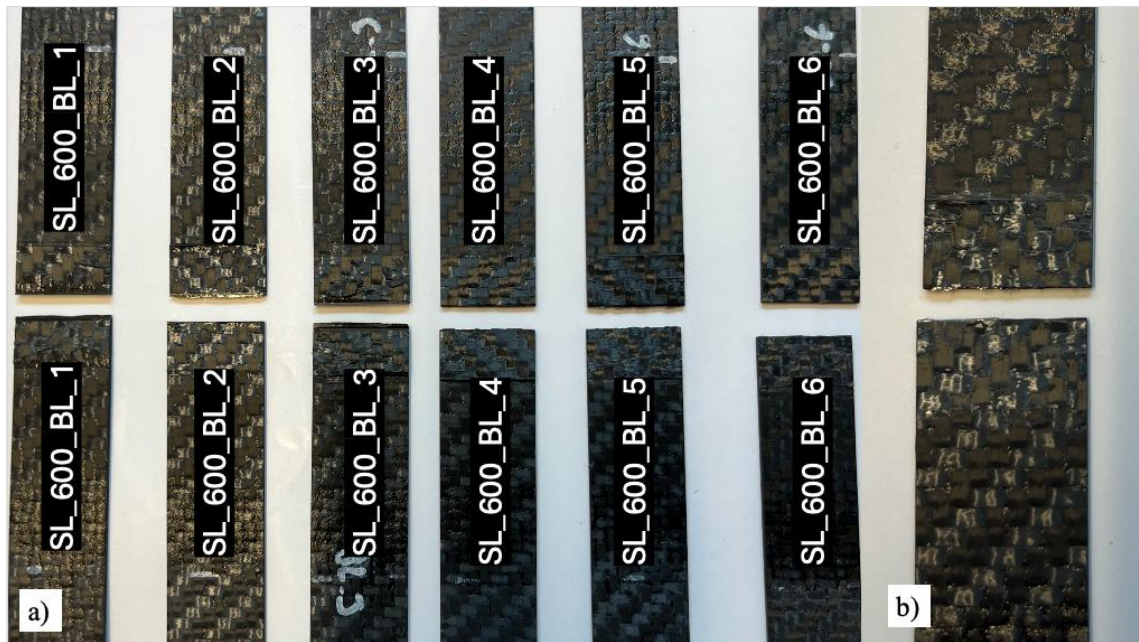


Figure 19 – Fracture surfaces for a) - SL_600_BL group. And b) -Up close fracture surface for one SL_600_BL sample.

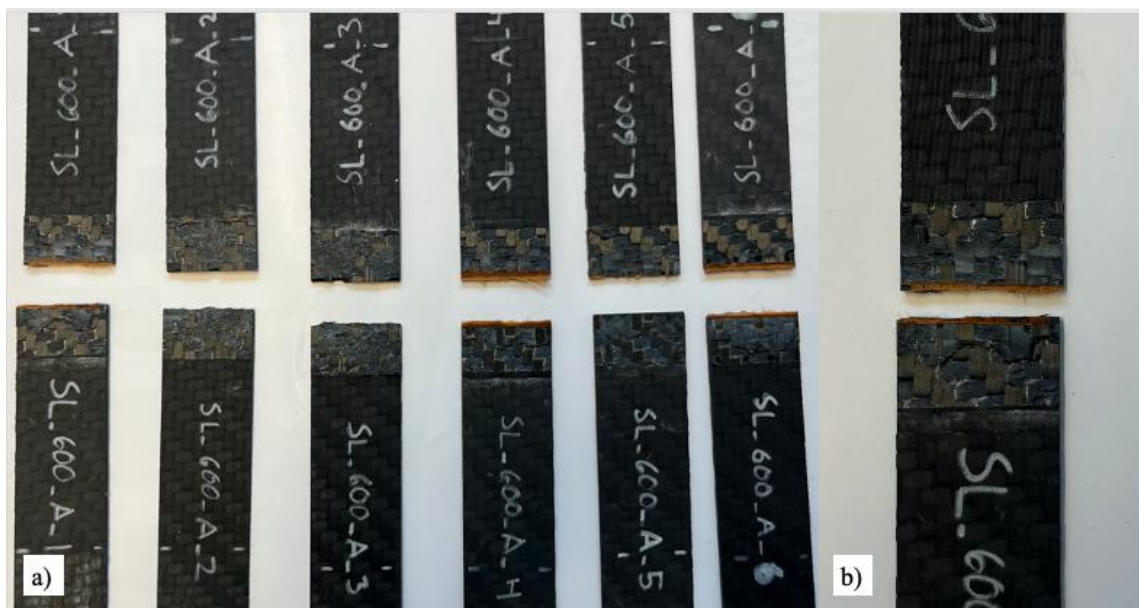


Figure 20 - Bonded surfaces post shear for a) - SL_600_A group. And b) -In depth bonded surface for one SL_600_A sample.

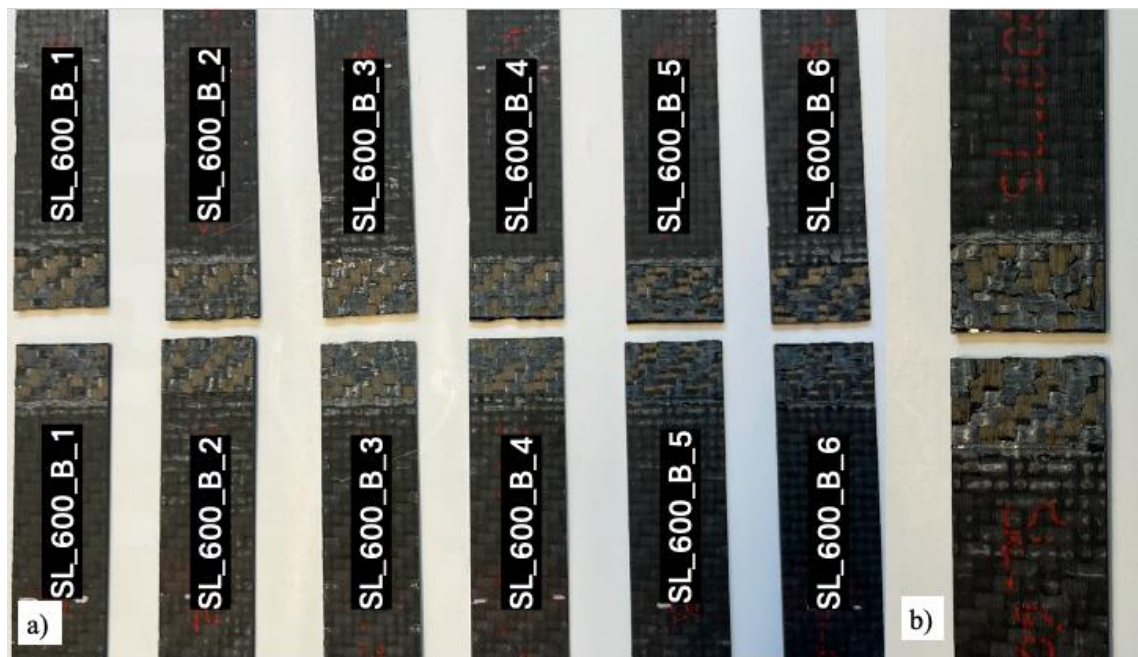


Figure 21 – Fracture surfaces for a) - SL_600_B group. And b) -Up close fracture surface for one SL_600_B sample.

Table 2 - Measured dimensions for SL specimen in the 600 group.

SL	2h (mm)	h (mm)	Ol (mm)	W (mm)	A (mm^2)	L (mm)	h_b (mm)	Done	Max (N)	Max Stress (Mpa)	Note
600_BL_1	3,58	1,58	12,8	25,2	322,56	99,9	0,42	SANT			no data
600_BL_2	3,56	1,61	13	25,2	327,6	99,75	0,34	SANT	3340	10,1953602	
600_BL_3	3,65	1,57	13	25,15	326,95	100,1	0,51	SANT	3294	10,074935	
600_BL_4	3,45	1,62	12,5	25,15	314,375	99,9	0,21	SANT	3212	10,2170974	
600_BL_5	3,37	1,65	13	25,15	326,95	100	0,07	SANT	3709	11,3442422	
600_BL_6	3,6	1,62	12,7	25,25	320,675	99,3	0,36	SANT	3044	9,49247681	
600_BL_7								FALSKT			
mean	3,535	1,60833333	12,8333333	25,1833333	323,185	99,825	0,31833333		3319,8	10,2648223	
600_A_1	3,86	1,8	14	24,8	347,2	99,6	0,26	SANT			no data
600_A_2	3,74	1,82	13,2	24,9	328,68	99,55	0,1	SANT	5500	16,7336011	
600_A_3	3,67	1,77	13,3	24,85	330,505	99,8	0,13	SANT	4998	15,1223128	pealply left?
600_A_4	3,91	1,82	14	24,9	348,6	100	0,27	SANT	4529	12,9919679	
600_A_5	3,7	1,77	13,2	25,05	330,66	99,3	0,16	SANT	4661	14,0960503	
600_A_6	3,85	1,8	14	24,9	348,6	99,65	0,25	SANT	5260	15,0889271	pealply left?
600_A_7								FALSKT			
mean	3,78833333	1,79666667	13,6166667	24,9	339,040833	99,65	0,195		4989,6	14,8065718	
600_B_1	3,5	1,71	13,9	25,2	350,28	100,25	0,08	SANT	4755	13,5748544	
600_B_2	3,45	1,66	13,9	25,15	349,585	100,25	0,13	SANT	5566	15,9217358	
600_B_3	3,45	1,68	13,8	25,1	346,38	100	0,09	SANT	4655	13,4389976	
600_B_4	3,46	1,7	14,3	25	357,5	100,1	0,06	SANT	5210	14,5734266	
600_B_5	3,5	1,72	14	25,2	352,8	100,25	0,06	SANT	5119	14,5096372	
600_B_6	3,53	1,73	14,2	25,1	356,42	100,05	0,07	SANT	4747	13,3185568	
600_B_7								FALSKT			
mean	3,48166667	1,7	14,0166667	25,125	352,160833	100,15	0,08166667		5008,66667	14,3524708	

4.2.5. SL Tx - Plots

Fel! Hittar inte referenskölla. a)- c), showcases the shear force (N) for the individual single lap specimen of the Textreme layup. These are plotted against its corresponding displacement (mm) for all groups of preparation. The test is all compared in the boxplot **Figure 22 d)**, based on max, min and mean shear force.

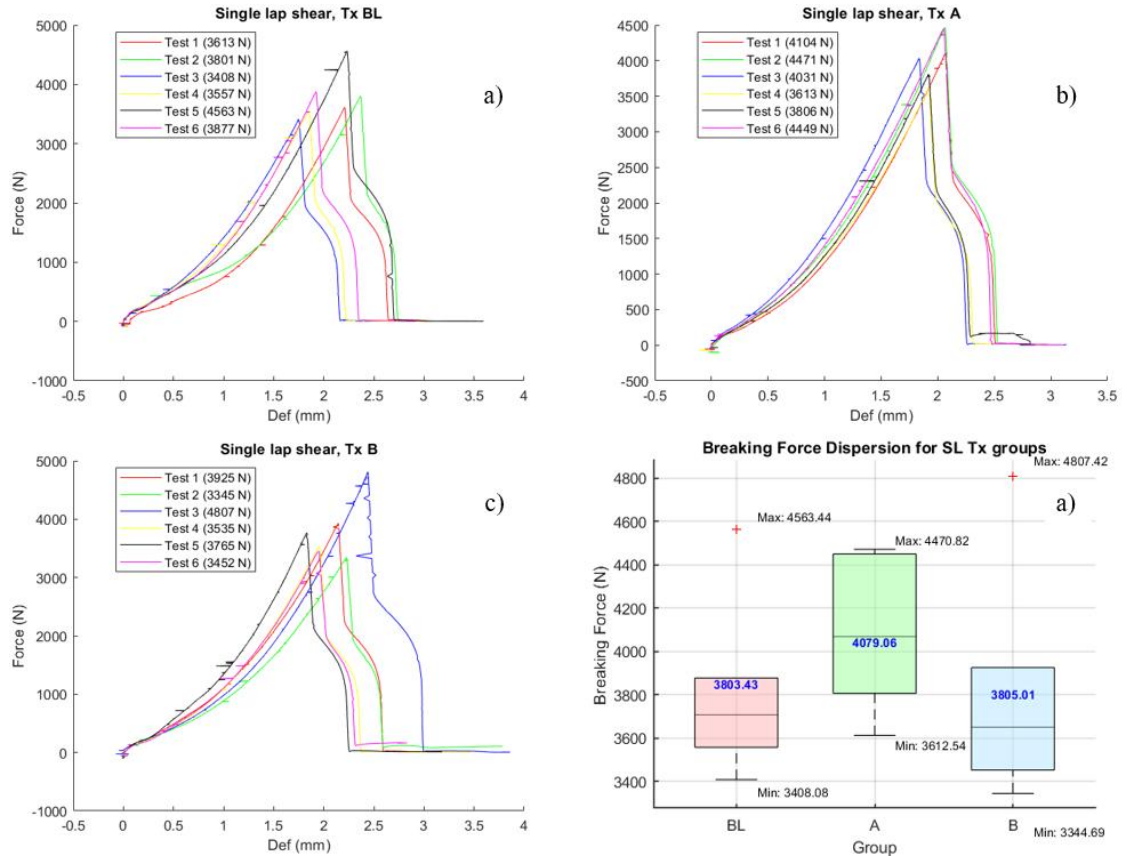


Figure 22 - Force/Displacement plot for SL_Tx_BL specimen a), A specimen b), B specimen c), Box diagram showing dispersion for all Tx tests d).

4.2.6. SL 600 – Fracture surfaces and dimensions

Dimensions for all SL Tx specimen as seen in **Table 3**. Measured dimensions are a mean thickness of the assembly $2h$. One substrate thickness h . After which bond thickness h_b can be calculated. Measured is also width w , and overlap Ol and length l . Further, fracture surfaces for Tx group post tensile testing is shown in below. Showcasing the different failure mechanism that are present for the earlier mentioned group.



Figure 23- Fracture surfaces for a) - SL_Tx_BL_group. And b) -Up close fracture surface for one SL_Tx_BL sample.

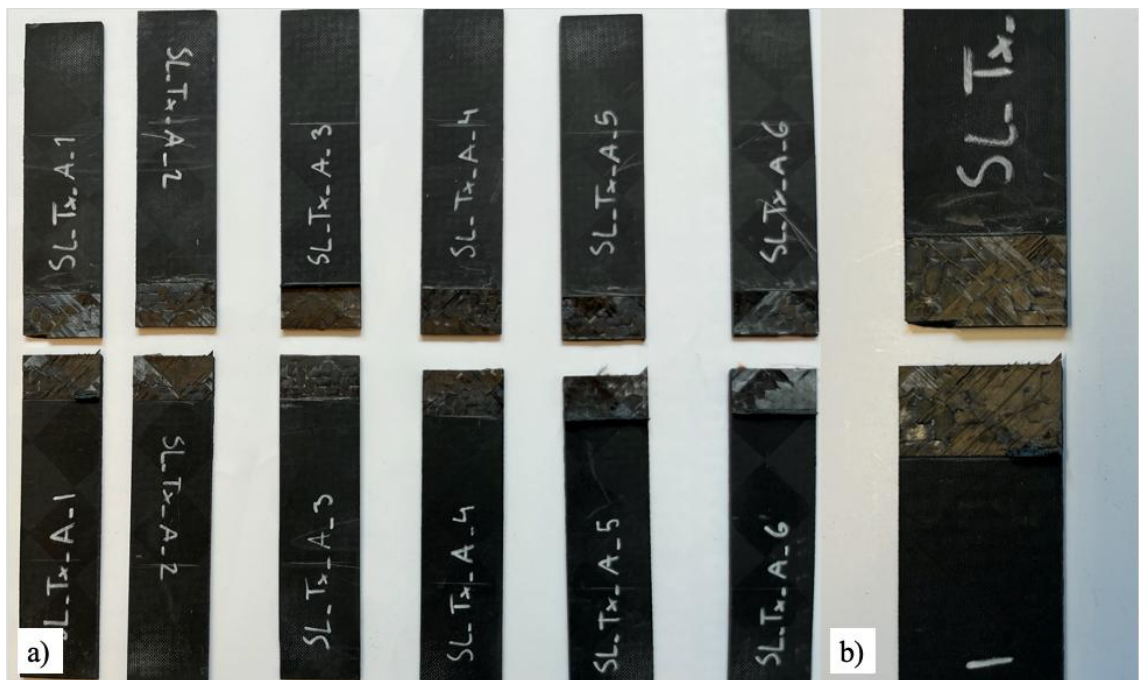


Figure 24 - Fracture surfaces for a) - SL_Tx_A_group. And b) -Up close fracture surface for one SL_Tx_A sample.

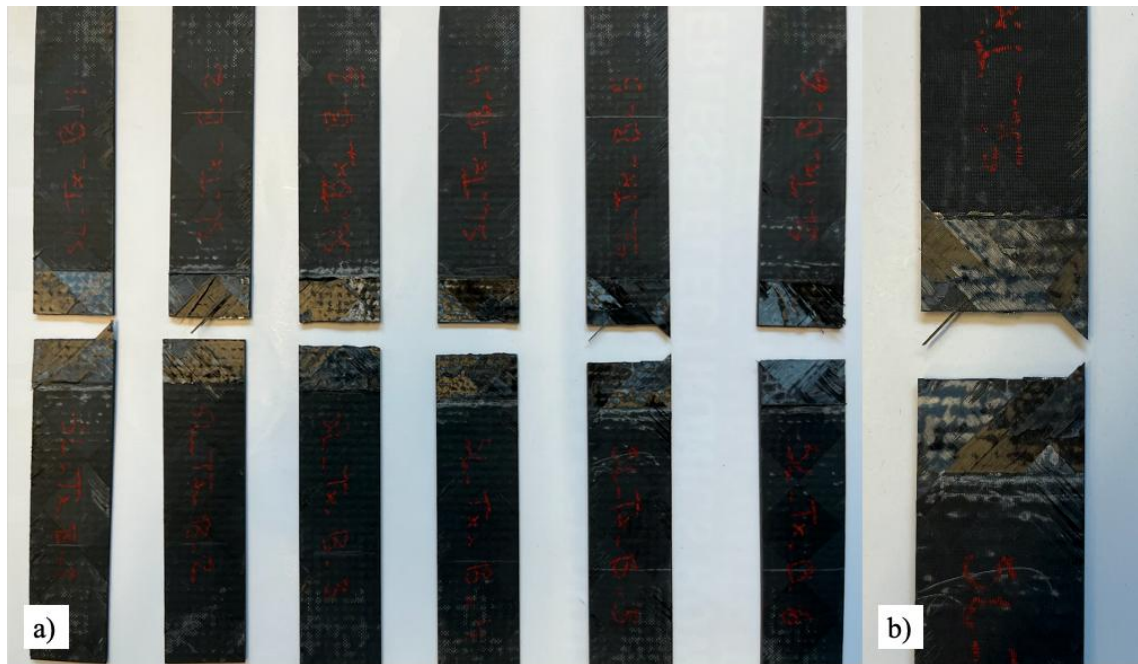


Figure 25 - Fracture surfaces for a) - SL_Tx_B_group. And b) – Up close Fracture surface for one SL_Tx_B sample.

Table 3 - Measured dimensions for SL specimen in group Tx.

SL	2h (mm)	h (mm)	Ol (mm)	W (mm)	A (mm ²)	l (mm)	h_b (mm)	Done	Max (N)	Max Stress (Mpa)	Note
Tx_BL_1	4,4	2,09	13	25,05	325,65	100,2	0,22	SANT	3613	11,094734	
Tx_BL_2	4,25	2,02	13	25,2	327,6	100	0,21	SANT	3801	11,602564	
Tx_BL_3	4,3	2,01	12,9	24,9	321,21	100,35	0,28	SANT	3406	10,603655	
Tx_BL_4	4,3	2,04	12,75	25,2	321,3	100	0,22	SANT	3557	11,07065	
Tx_BL_5	4,34	2,03	13,1	25,25	330,775	100,15	0,28	SANT	4563	13,794876	
Tx_BL_6	4,36	2,07	13,25	25	331,25	100,2	0,22	SANT	3877	11,704151	
Tx_BL_7								FALSKT			
mean	4,325	2,0433333	13	25,1	326,2975	100,15	0,2383333		3802,8333	11,755179	
Tx_A_1	3,97	1,95	13,7	24,8	339,76	99,8	0,07	SANT	4104	12,079115	
Tx_A_2	4,14	2	13,55	24,85	336,7175	99,8	0,14	SANT	4471	13,278193	Small edge
Tx_A_3	4,09	2,01	13,4	24,9	333,66	99,8	0,07	SANT	4031	12,08116	
Tx_A_4	4,02	1,98	13,1	24,75	324,225	99,8	0,06	SANT	3613	11,143496	
Tx_A_5	4,12	1,99	13,2	24,75	326,7	99,8	0,14	SANT	3806	11,649832	small edge
Tx_A_6	4,14	2,02	13,1	24,85	325,535	99,8	0,1	SANT	4449	13,666733	
Tx_A_7								FALSKT			
mean	4,08	1,9916667	13,341667	24,816667	331,09958	99,8	0,0966667		4079	12,363883	
Tx_B_1	3,95	1,94	13,15	25	328,75	99,9	0,07	SANT	3925	11,939163	
Tx_B_2	4,09	1,92	12,95	25,1	325,045	100,1	0,25	SANT	3345	10,290883	
Tx_B_3	3,9	1,91	12,85	25,1	322,535	99,85	0,08	SANT	4807	14,903809	
Tx_B_4	4,02	1,91	13,1	25,1	328,81	99,9	0,2	SANT	3535	10,75089	
Tx_B_5	3,95	1,94	13,3	24,95	331,835	100	0,07	SANT	3765	11,346	
Tx_B_6	3,97	1,92	12,9	25,2	325,08	100,1	0,13	SANT	3452	10,618925	
Tx_B_7								FALSKT			
mean	3,98	1,9233333	13,041667	25,075	327,00917	99,975	0,1333333		3804,8333	11,582101	

4.3. Modified Double Cantilever Beam

Following chapter cover results for the force – displacement curves of the 285-gsm layup, following the three different surface preparation for the MDCB in 4.3.1. To support the plots, results of the corresponding fracture surfaces and measured dimensions of the specimens are also covered in 4.3.2.

4.3.1. MDCB 285 - plots

Following chapter demonstrate the result from the peel test of the MDCB test specimens for the 285gsm layup. Presented are the force relative to the displacement for the groups of surface preparation Method BL, Method A and Method B in **Figure 26 a)-c)**. Extracted data are ultimate peeling strength F_{max} and mean peeling strength F_m . The three preparation methods are compared through force dispersions in **Figure 28**. In **Figure 27** it can be seen how F_m is measured.

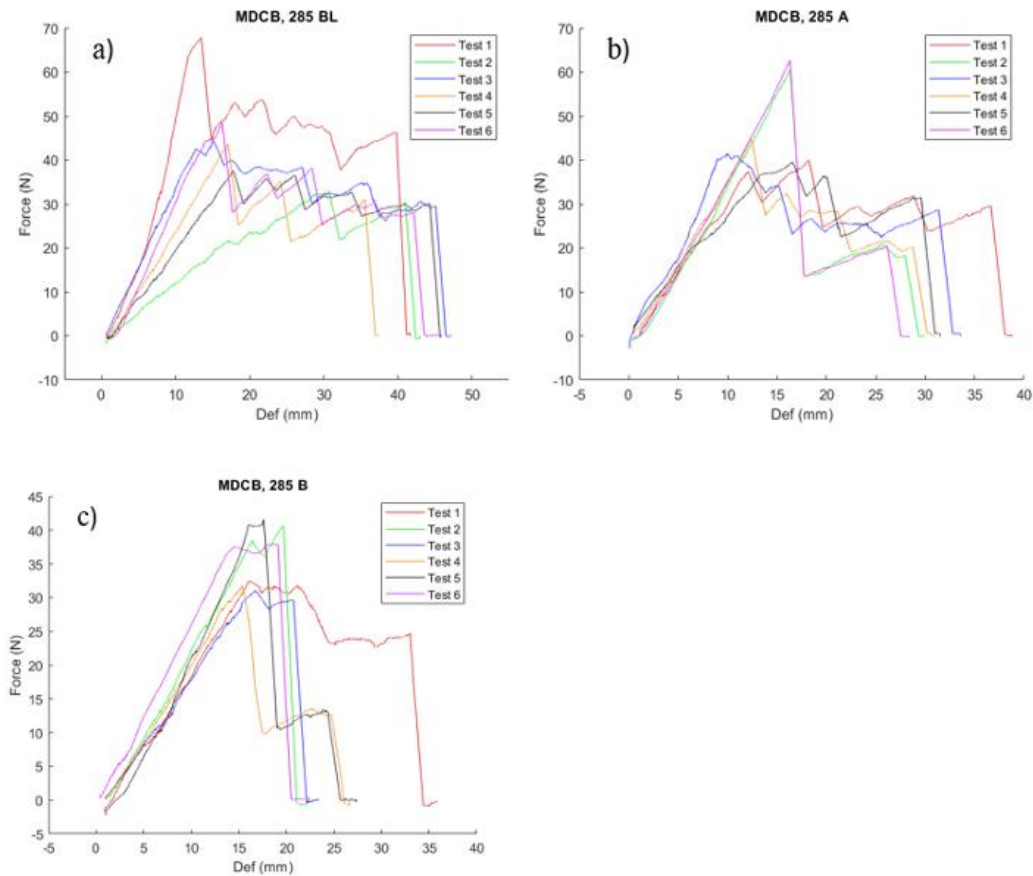


Figure 26 - Force/Displacement plot for MDCB_285 a) - BL specimens, b) - A specimen, c) - B specimen.

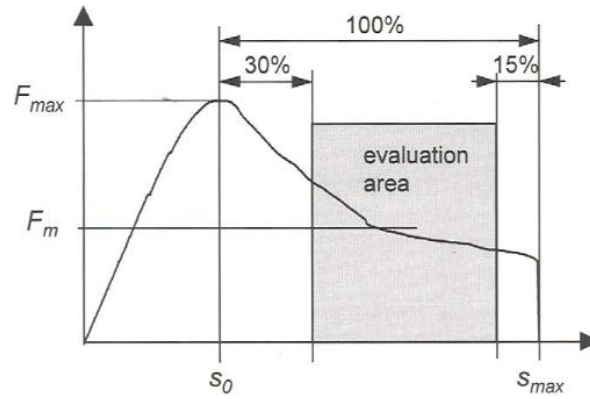


Figure 27 - Typical force/distance profile monitored during a peel test and illustration of the data evaluation from a force/distance profile of CFRP test specimen. [27]

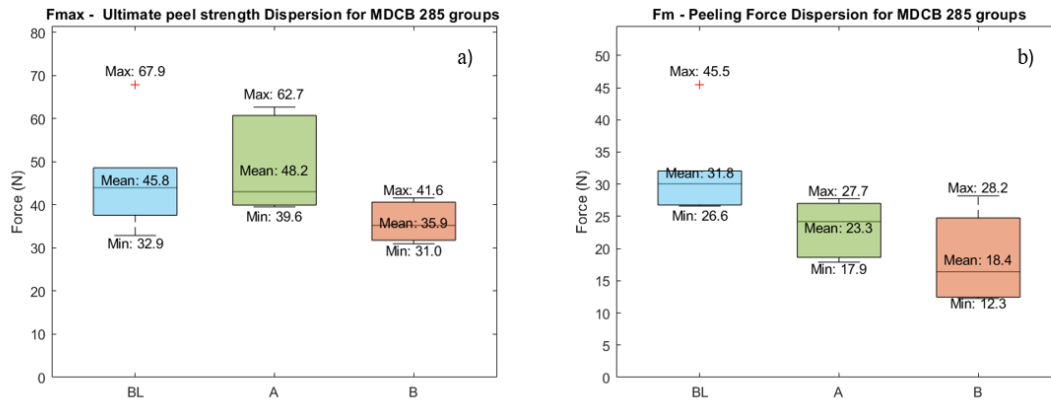


Figure 28 - Box diagram showing dispersion of a) – ultimate peel strength F_{max} and mean peeling force F_m for all Tx tests.

4.3.2. MDCB – Fracture surfaces and dimensions

Dimensions for all MDCB specimen as seen in **Table 4**. Measured dimensions are a mean thickness of the assembly $2h$. One substrate thickness h . After which bond thickness h_b can be calculated. Measured is also width w and initial displacement δ . Further, fracture surfaces for Tx group post tensile testing is shown in **Fel! Hittar inte referenskälla.-28** below. Showcasing the different failure mechanism that are present for the earlier mentioned group.

Table 4 - Measured dimensions for MDCB specimen in group 285

MDCB	2h(1)	2h(2)	2h(3)	2h avg	h (mm)	w (mm)	δ_0 (mm)	h_b(mm)	Done	Fmax(N)	Fm (N)
285_BL_1	3,49	3,47	3,42	3,46	1,58	24,8	0,9	0,3	☑	67,92	45,46
285_BL_2	3,35	3,31	3,33	3,33	1,59	24,8	0,6	0,13	☑	32,91	26,77
285_BL_3	3,5	3,48	3,41	3,463333	1,6	24,9	0,7	0,28	☑	44,32	32,06
285_BL_4	3,34	3,34	3,31	3,33	1,6	24,75	0,5	0,14	☑	43,68	26,62
285_BL_5	3,42	3,4	3,38	3,4	1,58	24,75	0,8	0,24	☑	37,6	30,25
285_BL_6	3,4	3,37	3,35	3,373333	1,61	24,85	1,2	0,15	☑	48,58	29,85
285_BL_7									☐		
mean	3,416667	3,395	3,366667	3,392778	1,593333	24,808333	0,783333	0,2066667		45,835	31,835
285_A_1	3,58	3,62	3,75	3,65	1,6	24,85	1,2	0,42	☑	32,47	24,75
285_A_2	3,57	3,59	3,61	3,59	1,61	24,9	0,3	0,37	☑	40,62	17,59
285_A_3	3,52	3,6	3,7	3,606667	1,62	24,85	1	0,36	☑	31	28,19
285_A_4	3,5	3,5	3,51	3,503333	1,61	24,95	0,5	0,28	☑	31,81	12,44
285_A_5	3,46	3,64	3,74	3,613333	1,61	24,8	0,5	0,42	☑	41,6	12,25
285_A_6	3,55	3,51	3,3	3,453333	1,61	24,9	0,5	0,29	☑	38,01	15,22
285_A_7									☐		
mean	3,53	3,576667	3,601667	3,569444	1,61	24,875	0,666667	0,3566667		35,91833	18,40666667
285_B_1	3,34	3,38	3,4	3,373333	1,39	24,75	0,9	0,6	☑	39,97	27,74
285_B_2	3,5	3,51	3,43	3,48	1,38	24,95	1,2	0,75	☑	60,75	18,63
285_B_3	3,05	2,94	3,06	3,016667	1,37	25	1,05	0,2	☑	41,46	25,13
285_B_4	3,08	3,1	3,12	3,1	1,37	25	1	0,36	☑	44,66	23,27
285_B_5	3,34	3,38	3,29	3,336667	1,39	24,9	1,2	0,6	☑	39,56	27
285_B_6	3,5	3,5	3,38	3,46	1,38	24,95	0,4	0,74	☑	62,69	17,88
285_B_7									☐		
mean	3,301667	3,301667	3,28	3,294444	1,38	24,925	0,958333	0,5416667		48,18167	23,275

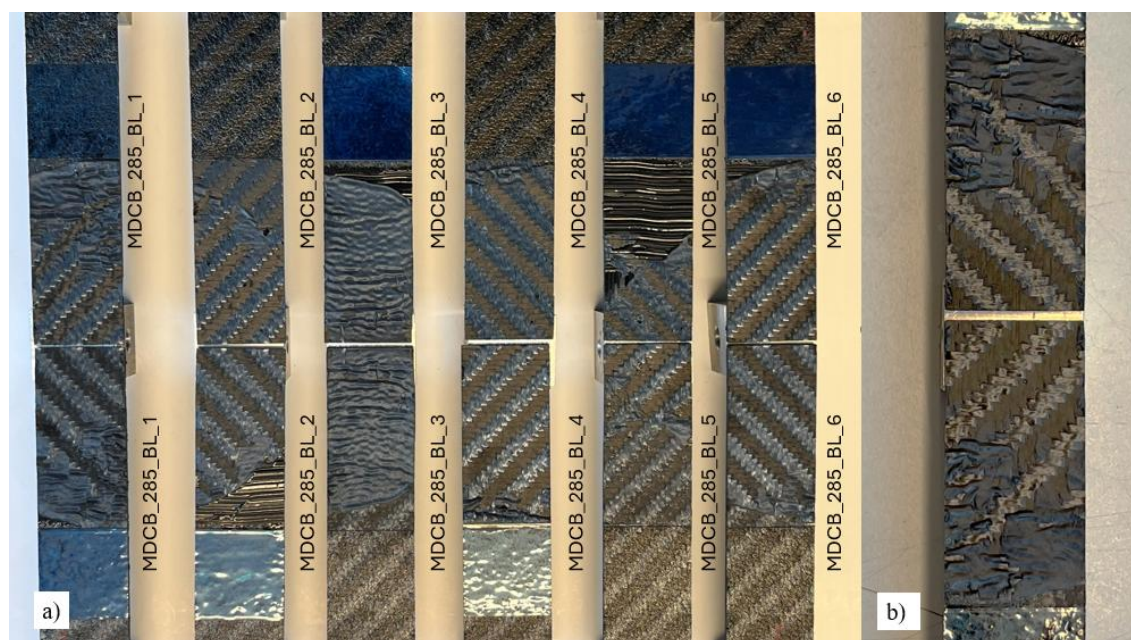


Figure 29 - Fracture surfaces for a) - MDCB_285_BL_group. And b) – Up close Fracture surface for one MDCB_285_BL sample.

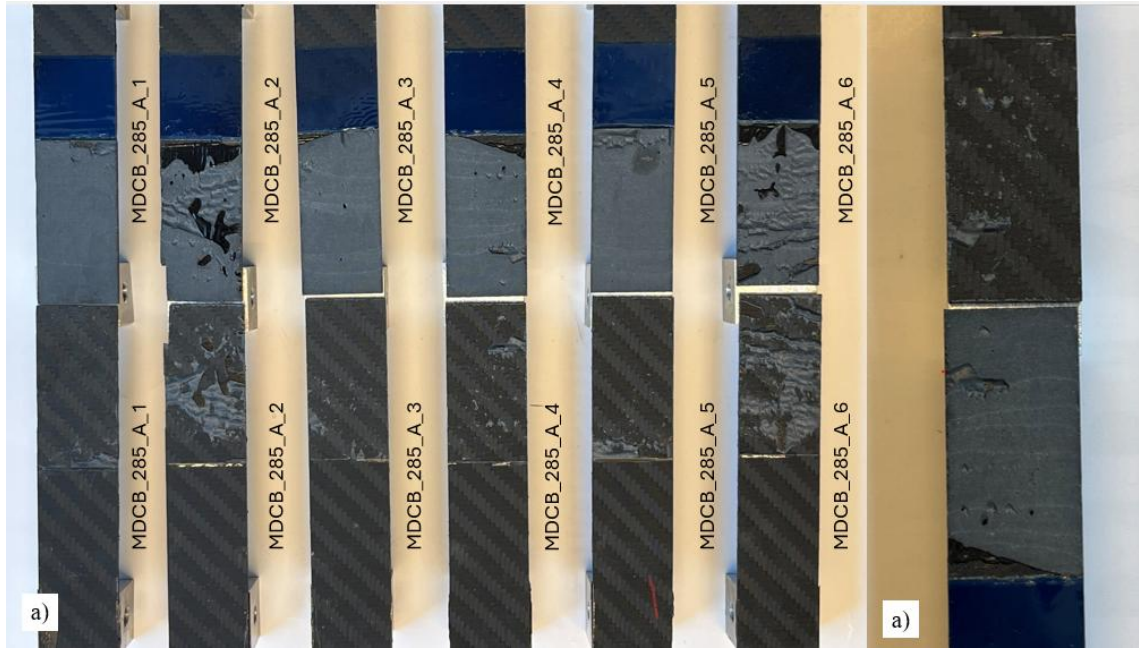


Figure 30 - Fracture surfaces for a) - MDCB_285_A_group. And b) – Up close Fracture surface for one MDCB_285_A sample.

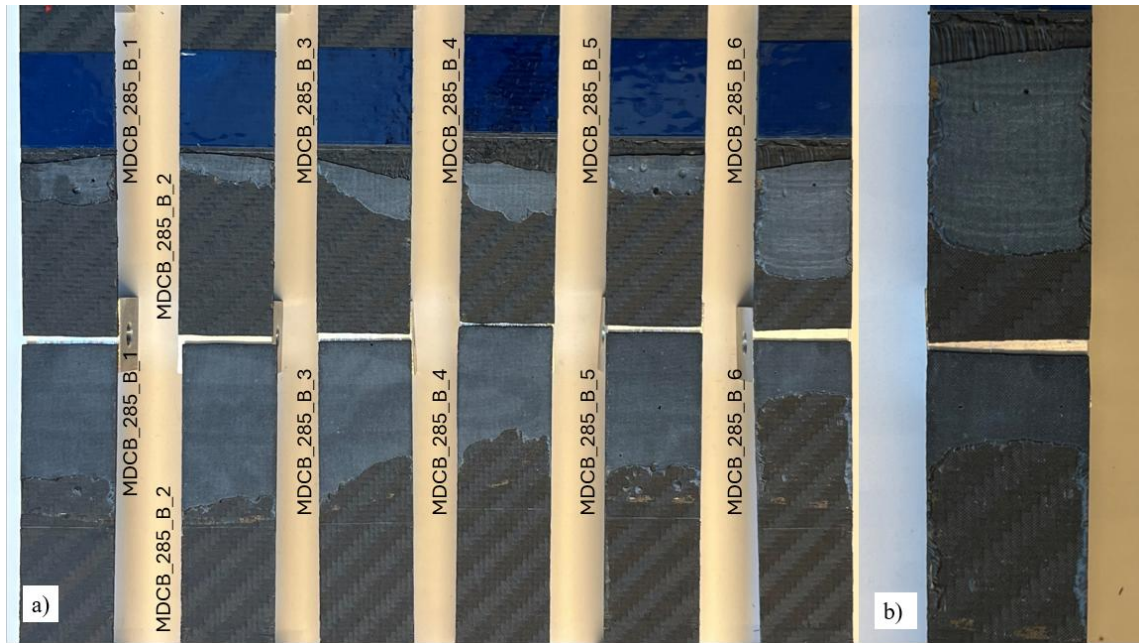


Figure 31 - Fracture surfaces for a) - MDCB_285_B_group. And b) – Up close Fracture surface for one MDCB_285_B sample.

5. Discussion and conclusion

5.1. FEM

Simulated stresses from 4.1 using the finite element methods shows to be a substantially bit higher compared to those of the physical tests. This is likely to be improved by better FEM modelling skills. Since the software HyperWorks was learned from scratch solely for this thesis, the learning curve constrained the quality and time that it took to model and troubleshoot the model. Therefore, no simulations are used to predict the physical tests in terms of actual peel or shear strength. The simulations are rather used to observe the stress distribution to help and better understand the different failure modes of the sheared tests. The simulation further helps to motivate and finalize the design for the loading blocks for the MDCB indicating that the bonded area between block and specimen would be sufficiently large to not be affected by the applied force and skew with the results.

5.2. Shear and Peeling

Following segment covers the analysis of the result displayed in the force-displacement graphs for both SL and MDCB test, along with corresponding box diagrams for both types.

5.2.1. SL 285 - Plots

The results from the single lap specimens show that for the 285 gsm group in **Figure 14** - Force/Displacement plot for SL 285 BL specimen a), A specimen b), B specimen c), Box diagram showing dispersion for all 285 tests d). there is quite some slip of the specimen in the grippers that can be seen as larger displacements without any larger increases in force. i.e. flatter plots compared to the otherwise quite spiky plots. This can largely be traced to the smooth finish is achieved due to the manufacturing process. The additional module shown in **Figure 11 b)** where used for this group of tests which has a fixed gripping load compared to the self-aligning grippers who grip tighter the more you pull. Therefore, for larger value of shear force, more slip can be indicated near the peak like for test 4 for both method A and B test. It can be observed in **Figure 14 a)-c)** that there is a relatively large spread in shear force between test prepared in the same way with a spread larger than 1644 N, 2324 N and 3227 N for BL, A and B respectively. Despite this, the majority of test results are kept within the range of 25-75 percentile of their respective cluster with the exception for BL group that have one outlier. **Figure 14 d).** Is showing that specimen subjected to surface preparation A and B both on average reached a higher shear strength compared to the BL treatment for the 285gsm layup. With method A and B showing higher max shear forces compared to BL with method A showing a mean shear force 20%, and method B 28% higher, relative to method BL. It is to be said that the lowest shear force achieved from a specimen was prepared with the B method as well.

5.2.2. SL 600 - Plots

The plots of specimens in the 600-gsm group presented in **Figure 18 a)-c)** indicate that the slip for this group overall was reduced. This is likely due to the module in **Figure 11 b)** being removed since thoroughly post processing in terms of sanding and cleaning was performed to the specimen to get a surface course enough that the grippers would get an initial bite of the specimen. The dispersion of shear force for the 600 gsm also show to be less and closer packed compare to the 285-gsm group. From **Figure 18 b)** it can be seen that the shear forces produce a range of 665 N, 971 N and 911N for method BL, method A and method B respectively. This, along with the overall higher shear forces for method A and B (BL showing somewhat lower results). Can likely be attributed to the 600-gsm layup being slightly thicker and of a stronger material compared to the 285 group. Another possible factor is again the removal of the module in **Figure 11 b)** which subsequently would allow the machine more in line with the specimen centre axis compared to the module which pulls the substrates slightly off axis. Both of these factors should result in a higher resistance against bending that otherwise are common for single lap bonds. Resulting in peeling at the edge of the bond and can cause earlier failure. Something that is well documented in literature 2.3.1 and can be observed in the simulations in **Figure 13**. Finally. Just as for the 285 group, surface preparation method A and B both handle higher shear forces on average compared to preparation method BL. With method A and B producing shear forces 50% and 51% higher compared to method BL on average. And yet again A and B showing similar performance.

5.2.3. SL Tx - Plots

The third layup version Textreme Tx demonstrates in **Figure 22 a)-c)** similar to the 600-gsm group that slip is less present compared to the 285 group. Just as for the 600 group the Tx test are performed with the self-aligning grippers and should therefore experience less slip. However, compared to the 600-gsm test, the dispersion in shear forces are for Tx samples are a bit with the spread across max and min shear forces ranging from 1155 N, 858 N and 1462N. This is in fact less of a spread over all compared to the 285 gsm group, but since these result are more compactly grouped in general, one test being a little higher as in the case for test 5 in **Figure 22 a)** and test 3 in **Figure 22 c)**. Making these tests fall outside of the 25-75 percentile range and be marked as outliers as seen in **Figure 22 d)**. While for 285 tests, they are more spread out over the range and therefore is not picked up as outliers. Even though the Tx specimens theoretically should be even stronger against bending compared to the 600 group, the preparation methods A and B in the Tx group performed worse compared to the corresponding preparation method in the 600 group. This is likely due to the different type of fibres for the Tx posing a new weakest point not present for 600 group. More on this in 5.3. Lastly, surface preparation method A prove to perform better on average for Tx layups by 7.2% Continuing the trend by the other two layups. Although being by not as much as for the other two groups. As for method B, it deviated compared to the other

layups by only being level with the BL method, deviating by less than one per mile relative to each other. However, for all tests performed, preparation method A and B has either performed better or equal to that of the BL method.

5.2.4. MDCB 285 – Plots

For the MDCB test, **Figure 26 a)-c)**. It can be seen that compared to the fore-displacement graphs of SL, the MDCB test show higher variations in amplitude, displacement and over all trajectory. The larger variations can likely be seen as a result of the longer testing range. Analysing a larger bonding area allows more fluctuations to occur. Noticeably is that method BL show proof of an outlier test for both F_{max} and F_m by being outside of the 25-75 percentile range. Comparing the results from **Figure 26 c)**. The trend that could be observed for the SL where the two-preparation methods A and B clearly performed equal or better compared to the BL, now looks to indicate a relative even performance across the three preparation methods and even a slight decrease in performance for method A and B. Especially considering the mean peeling force F_m , where method A and B show a 27% and 41% decrease in mean peeling strength relative the BL method. For ultimate peel strength F_{max} , the difference where an increase by 5% for method A and a decrease by 21%. It is to be said that for peel test performed on specimen produced with method B consist of three test that was separated quite quick and therefore could not produce a sufficient peeling distance to analyse. The mean for that particular method should therefore be questioned. Also, for forces this small. Even minor variations like one newton can result in quite large swings, percentage wise. The collective result for the peeling test could indicate a reduced performance for preparation method A and B relative to BL. However, to confirm this, peel tests on the other layups would need to be performed.

5.3. Fracture surfaces

Following chapter include analysis of the fracture surfaces following the shear test and peeling test for both the SL specimens. As well as the MDCB specimen.

5.3.1. Fracture surfaces – Shearing

Observing the fracture surfaces from the 285_BL group through. The different mechanisms that can be indicated are almost exclusively, a mixture between cohesive failure within the adhesive and cohesive failure within the CFRP. For both matrix and fibre failure. Though difficult to identify from the figures. This leaves both exposed carbon and adhesive on both substrate of the fracture visible through the high contrast fibres in **Figure 15**. For the other fracture surfaces **Figure 16** and **Figure 17** associated to the A and B method. The same types of failures are identified. A larger part of matrix failure can be seen here, leaving larger pieces of adhesive unlit. Matrix failure, can initially look like fibre failure but one side is typically a little paler and more different in texture from the thin layer of epoxy.

For the BL method of the 600-gsm group, observing **Figure 19**. Show failure mechanisms almost identical to BL 285 specimens. Showing a mixture of a mixture between cohesive failure within the adhesive and cohesive failure within the CFRP. For some minor part. Some deeper dark zone can be identified. This is zones were proper adhesion between the two surfaces was not achieved. Also, for 600 gsm method A and B fracture surfaces in **Figure 20** and **Figure 21** are similar to corresponding surfaces in the 285 group. Potentially a higher degree of cohesive failure within the adhesive leaving several smaller fraying spots.

Some interesting observations can be made once the fracture surfaces of the Tx group are performed. For the BL method of the Tx group, see **Figure 23** The cohesive failure within the CFRP is clearly spotted when the thin layer of Textreme is sheared of and exposes the 600-gsm twill underneath. Obviously with some adhesive still left on both substrates, displaying failure in the adhesive as well. The shearing of fibres is also coherent through **Figure 24** and **Figure 25** with the Collectively through the Tx group is that fibre fracture is way more present that for the other layup groups. By the Textreme ply being the weakest point instead of the adhesive or bond. This is also likely the reason for the overall reduced shear strength of the Tx specimen and the reason that the results over the different surface preparation methods turn out more even.

NOTE: For none of the SL tests were adhesive or interfacial failure ever present.

5.3.2. Fracture Surfaces – Peeling

Evaluating **Figure 29**. A mix of failure mechanism are present and can better facilitate examination of the fracture surfaces due to the larger bond surface compared to the shear tests. Similar to the BL shear test, The BL peel test showcase a mixture of different failures. The deep darker areas indicate that the adhesive haven't been properly bonded to both specimens. Featured is also cohesive failure, both between adhesive and CFRP. An example can be seen in **Figure 29 b)** where the split adhesive is shown from one side and the exposed fibres, stripped from epoxy comes next.

Moving on to the fracture surface of method A of the 285 group. Interesting observations in **Figure 30** is that the fist examples of adhesive or interfacial failure where the adhesive splits from the CFRP and epoxy without tearing anything away. On the smooth surface of the remaining adhesive, white lines can be seen horizontally. These are marks left as a result of the peeling, releasing the surface bit by bit. Further, more non-bonding and breaking of the adhesive can are also present

Lastly, **Figure 31** presents the method B surface fracture. Across all specimens in this group, a behaviour can be seen of first handling some load before the adhesive is torn and then peeled in one segment until total separation. This is similar to **Figure 30** even more pronounced or interfacial failure. As this is observed exclusive to the two-preparation methods A and B.

Indicating that poorer adhesion might be achieved with the two-method compared to a BL method at least from a peeling load case.

As a final note. The analysis of fracture surfaces with solely the naked eyes leaves room for a lot of interpretation since most of the failures look very similar and easy to make mistakes. On a broader scale one can identify the types of failure but to make a deeper conclusion about the fracture surfaces, the surfaces should be analysed with microscope. For example, Scanning Electron Microscopy SEM.

5.4. Dimensions

Observing the collective tracing of the geometries through **Table 1-Table 4**. In general, it can be seen for a lot of dimensions, that tolerances that the ISO standards request are difficult to achieve for all dimensions. The bond thickness for all specimens are one such thing. Both ISO 25217:2009 [30] and ISO 4587:2003 [29] recommend a bond thickness of 0.2 mm $\pm$ 0.1 mm. However early in the process it was decided that the manufacturing of specimen would emulate the manufacturing procedure that are carried out at Blacking today so that the result in a high degree as possible could carry over to their production. This meant, among others, to not include spacers in the adhesives to sustain the desired thickness. The adhesive, does by itself contain glass balls of 0.05 mm. in diameter. Ensuring that there always is 0.05 as bare minimum for any joint. However, with the usual manufacturing procedure, after surface preparation is to apply adhesive through a nozzle and let the adhesive distribute evenly by applying little more than what is needed. Attach the second part, and let the adhesive spread out from the pressure and then off course clean the edge. Therefore, this was the approach used for this project as well. The most important dimension for the performance of the bond apart from bond thickness

5.5. Challenges

To produce all the 63 SL specimen plus the 21 MDCB specimens, a substantial time and effort of the thesis was dedicated to traveling, manufacturing as well as pre-and post-processing. Subsequently removing focus from other steps in the project such as FEM work, report writing and analysis.

Other challenges included the maintaining of tolerances. Observing the dimensions for all types of test-layup combinations. It is evident that a large portion of the test specimens in one way or another deviate from the desired tolerances even if high great care and precision is taken throughout the project. This could possibly be aided by using some rig to help maintain the correct distance of overlap. As well as keep an evenly distributed load over the bond. As well as allow for efficient edge cleaning. Spacers in the adhesive, although decided not to be pursued for this project could be usefully to sufficiently control a good bond thickness and maintain it throughout the extension of the MDCB peel for example.

5.6. Further work

To proceed with this the findings from this project, further peel-test should be performed for the two other layups that were tested for SL as well. This would allow for better comparison between peeling results. As well as adding credibility to the comparison in a similar fashion to the larger set of SL specimen. When further research has been performed. To further try to eliminate potential errors in the manufacturing of the samples. Some type of rig could be manufactured to make sure tolerances are actually kept throughout the manufacturing. To properly analyse the failure mechanisms of the bonded joints, future work could also explore microscopy of the fracture surfaces to more closely define where each failure mechanism take place and where they are initiated.

6. Summary and Conclusions.

From the discussion, it can be concluded that both surface preparations, method A and method B for single lap bonded joints, on average gives rise to a lap shear strength greater than what was measured from traditional sanding BL. This whilst still considering influencing factors during manufacturing and test execution. Although indicating that surface preparation method A and method B results in a peel strength equivalent or lower than that of conventional sanding BL. The obtained data is insufficient to draw a definitive conclusion on whether or not the BL method is fit to be substituted for method A or B in the Blackwing production. Further peel test on corresponding layups as were tested for single lap shear are therefore suggested to meet a final conclusion.

Result from shear test, indicate that it would be feasible for Blackwing to proceed with an intention of substituting traditional sanding BL the production given that further peel test indicates promising results. A physical validation of surface preparation A and B on a production piece should also be performed as validation before further implementation.

The result of this thesis has aided Blackwing in the pursuit of substituting sanding as surface preparation for gluing of parts such as the wings and fuselage. Thus, taking one step closer towards a cheaper and shorter production. The thesis has further provided information on adhesives in industry and its use with CFRP components. Subsequently bridging the gap between and R&D and production.

7. References

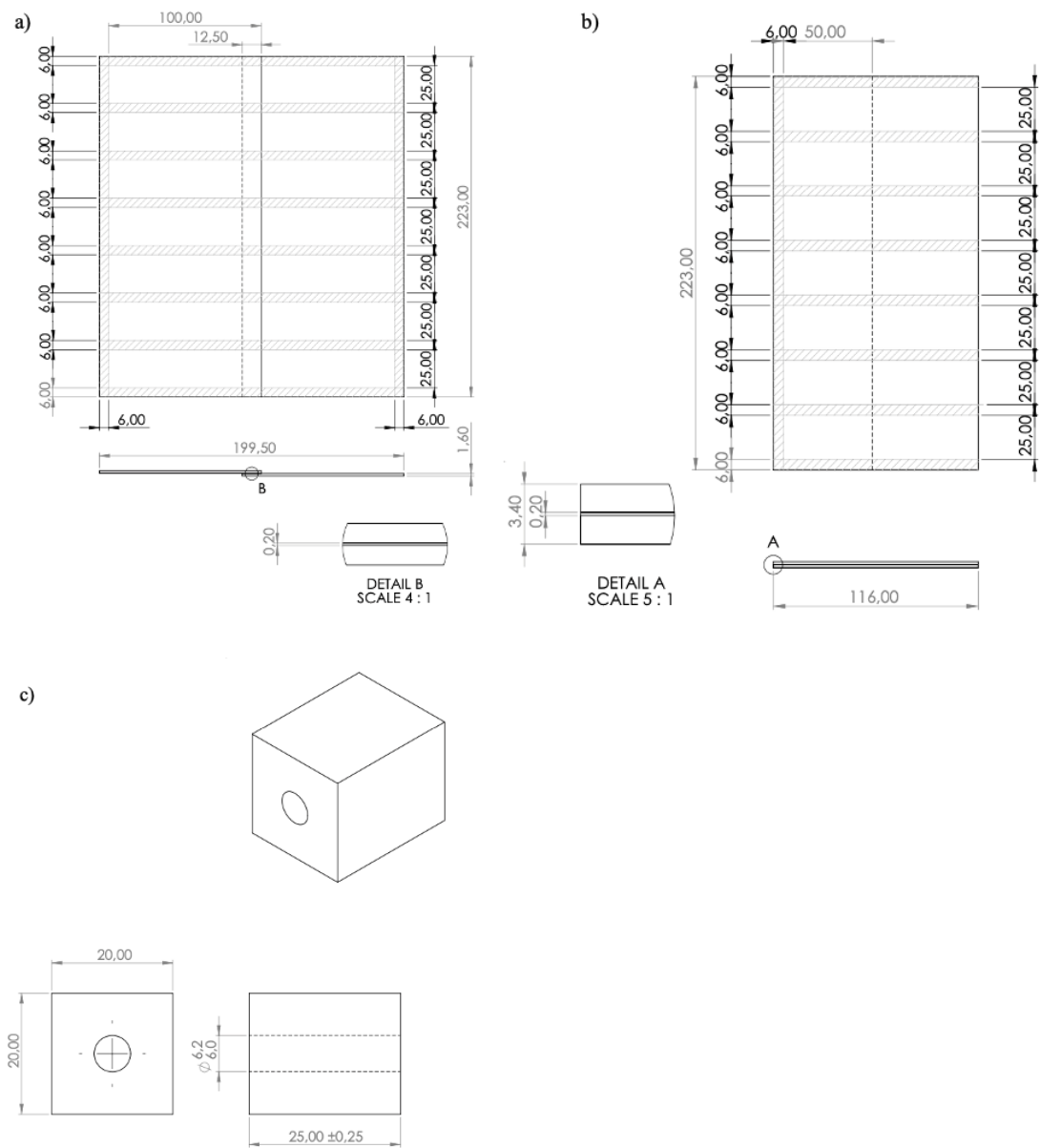
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Appendix

Appendix A – Technical Drawings

Technical drawing showcasing the cutting procedure for a) SL specimen and b) MDCB specimen and c) technical drawing of the loading block for the MDCB.



Appendix B – MATLAB code for plotting of data

Generalized MATLAB code for plotting of a) - force (N) and displacement (mm) for both SL, MDCB and b) - box diagrams for both SL and MDCB tests. (Here SL 285 is used as an example).

NOTE: AI have been used as a library for MATLAB code, aiding plotting of data. And also c)-.code for generating result matrix (Fm, Fmax) for MDCB.

a).

```
%Step 1 - Import data.
clc; clear all; clf;
t1 =
importdata("C:\Users\malmq\OneDrive\Skribbord\Tester\Theo\Raw_Force_Def_SL_2
85_BL_1_Date_2025_05_08_Time_13_27.txt");
t2 =
importdata("C:\Users\malmq\OneDrive\Skribbord\Tester\Theo\Raw_Force_Def_SL_2
85_BL_2_Date_2025_05_08_Time_15_05.txt");
t3 =
importdata("C:\Users\malmq\OneDrive\Skribbord\Tester\Theo\Raw_Force_Def_SL_2
85_BL_3_Date_2025_05_05_Time_16_43.txt");
t4 =
importdata("C:\Users\malmq\OneDrive\Skribbord\Tester\Theo\Raw_Force_Def_SL_2
85_BL_4_Date_2025_05_08_Time_15_24.txt");
t5 =
importdata("C:\Users\malmq\OneDrive\Skribbord\Tester\Theo\Raw_Force_Def_SL_2
85_BL_5_Date_2025_05_08_Time_15_52.txt");
t6 =
importdata("C:\Users\malmq\OneDrive\Skribbord\Tester\Theo\Raw_Force_Def_SL_2
85_BL_6_Date_2025_05_05_Time_15_06.txt");

%Step 2 - Shift x-axis (make sure all start @ 0mm displacement).
t1(:,2) = t1(:,2) + abs(t1(1,2));t2(:,2) = t2(:,2) + abs(t2(1,2));
t3(:,2) = t3(:,2) + abs(t3(1,2));t4(:,2) = t4(:,2) + abs(t4(1,2));
t5(:,2) = t5(:,2) + abs(t5(1,2));t6(:,2) = t6(:,2) + abs(t6(1,2));

%Step 3 - Convert to tables
t1_table = array2table(t1); t2_table = array2table(t2);
t3_table = array2table(t3); t4_table = array2table(t4);
t5_table = array2table(t5); t6_table = array2table(t6);

%Step 4 - Remove if necessary data in test before displacement X.X mm to
%account for any initial slip.
%t1_table = t1_table(t1_table.t12 >= X.X, :);
%t2_table = t2_table(t2_table.t22 >= X.X, :);
%t3_table = t3_table(t3_table.t32 >= X.X, :);
%t4_table = t4_table(t4_table.t42 >= X.X, :);
%t5_table = t5_table(t5_table.t52 >= X.X, :);
%t6_table = t6_table(t6_table.t62 >= X.X, :);
```

```

%Step 5 - Reset any adjustments from Step 4 back at 0 mm displacement
t1_table.t12 = t1_table.t12 - t1_table.t12(1);
t3_table.t32 = t3_table.t32 - t3_table.t32(1);
t5_table.t52 = t5_table.t52 - t5_table.t52(1);
t6_table.t62 = t6_table.t62 - t6_table.t62(1);

%Step 6 - Smoothing of data
t1_table("t13") = smoothdata(t1_table, "movmean", 100, "DataVariables",
"t11").t11;
t2_table("t23") = smoothdata(t2_table, "movmean", 100, "DataVariables",
"t21").t21;
t3_table("t33") = smoothdata(t3_table, "movmean", 100, "DataVariables",
"t31").t31;
t4_table("t43") = smoothdata(t4_table, "movmean", 100, "DataVariables",
"t41").t41;
t5_table("t53") = smoothdata(t5_table, "movmean", 100, "DataVariables",
"t51").t51;
t6_table("t63") = smoothdata(t6_table, "movmean", 100, "DataVariables",
"t61").t61;

%Step 7 - Plotting Force vs Displacement
figure(1); hold on;
title('Single lap shear, 285 BL', 'FontWeight', 'bold');
plot(t1_table.t12, t1_table.t13, 'r');
plot(t2_table.t22, t2_table.t23, 'g');
plot(t3_table.t32, t3_table.t33, 'b');
plot(t4_table.t42, t4_table.t43, 'y');
plot(t5_table.t52, t5_table.t53, 'k');
plot(t6_table.t62, t6_table.t63, 'm');

%Step 8 - Generate shear forces
maxForces_BL = [max(t1_table.t13), max(t2_table.t23), max(t3_table.t33),
...
               max(t4_table.t43), max(t5_table.t53), max(t6_table.t63)];

%Step 9 - Display them along with plot
legendStrings = {
    sprintf('Test 1 (%.0f N)', maxForces_BL(1)),
    sprintf('Test 2 (%.0f N)', maxForces_BL(2)),
    sprintf('Test 3 (%.0f N)', maxForces_BL(3)),
    sprintf('Test 4 (%.0f N)', maxForces_BL(4)),
    sprintf('Test 5 (%.0f N)', maxForces_BL(5)),
    sprintf('Test 6 (%.0f N)', maxForces_BL(6))
};
%xlim([a b]);
%ylim([a b]);
legend(legendStrings, 'Location', 'best');
xlabel('Def (mm)');
ylabel('Force (N)');

```

b).

```
%Step 1 - Loading max forces from force vs displacement plots
load('N_285_BL.mat'); % Ex: N_285_BL
load('N_285_A.mat'); % Ex: N_285_A
load('N_285_B.mat'); % Ex: N_285_B

%Step 2 - Collect and group data
data = [N_285_BL(:); N_285_A(:); N_285_B(:)];
groups = [repmat({'BL'}, length(N_285_BL), 1); repmat({'A'},
length(N_285_A), 1); repmat({'B'}, length(N_285_B), 1)];

%Step 3 - Generate boxplot
figure('Color', 'w')
boxplot(data, groups, 'Colors', 'k', 'Symbol', 'o', 'Widths', 0.6);
title('Boxplot av brottkrafter för grupperna BL, A och B', 'FontWeight',
'bold');
ylabel('Kraft (N)');
set(gca, 'FontSize', 11);
hold on;

%Step 4 - Naming and delegating data
groupNames = {'BL', 'A', 'B'};
groupData = {N_285_BL, N_285_A, N_285_B};

%Step 5 - Add the statistics
for i = 1:3
    gData = groupData{i};
    x = i; % Position
    gMax = max(gData);
    gMin = min(gData);
    gMean = mean(gData);
    gStd = std(gData);
    plot(x, gMean, 'r*', 'MarkerSize', 10, 'LineWidth', 1.5);

    % Text for the statistics
    yOffset = range(gData) * 0.05;
    text(x + 0.1, gMax + yOffset, sprintf('Max: %.0f N', gMax), 'FontSize', 9);
    text(x + 0.1, gMin - yOffset, sprintf('Min: %.0f N', gMin), 'FontSize', 9);
    text(x + 0.1, gMean, sprintf('Medel: %.0f N', gMean), 'Color', 'r',
'FontSize', 9);
    text(x + 0.1, gMean - 2*yOffset, sprintf('Std: %.0f N', gStd), 'Color',
[0.2 0.2 0.2], 'FontSize', 9);
end

hold off;
% Additional code may be added to make the plot more visually pleasing
```

c).

```
%% Max, mean - to calculate F_results
clc; clear all;

% Paths
test_files = {

"C:\\Users\\malmq\\OneDrive\\Skribbord\\Tester\\Theo\\Raw_Force_Def_MDCB_285
_BL_1_Date_2025_05_28_Time_11_09.txt",
"C:\\Users\\malmq\\OneDrive\\Skribbord\\Tester\\Theo\\Raw_Force_Def_MDCB_285
_BL_2_Date_2025_05_28_Time_13_16.txt",
"C:\\Users\\malmq\\OneDrive\\Skribbord\\Tester\\Theo\\Raw_Force_Def_MDCB_285
_BL_3_Date_2025_05_28_Time_13_41.txt",
"C:\\Users\\malmq\\OneDrive\\Skribbord\\Tester\\Theo\\Raw_Force_Def_MDCB_285
_BL_4_Date_2025_05_30_Time_11_02.txt",
"C:\\Users\\malmq\\OneDrive\\Skribbord\\Tester\\Theo\\Raw_Force_Def_MDCB_285
_BL_5_Date_2025_05_30_Time_11_42.txt",
"C:\\Users\\malmq\\OneDrive\\Skribbord\\Tester\\Theo\\Raw_Force_Def_MDCB_285
_BL_6_Date_2025_05_30_Time_12_16.txt"
};

% Shift in x to account for initial displacement.
% shifts = [x.x, x.x, x.x, x.x, x.x, x.x];

% Initiate result matrix: F1, F2, Fm, Fmax
F_results = zeros(length(test_files), 4);

for i = 1:length(test_files)
    raw = importdata(test_files{i});
    T = array2table(raw);
    T{:,2} = T{:,2} - T{1,2}; % Start from 0
    T{:,2} = smoothdata(T{:,2}, 'movmean', 100);
    T{:,3} = smoothdata(T{:,1}, 'movmean', 500);
    T{:,3} = T{:,3} - T{end,3};

    displacement = T{:,2} + shifts(i);
    force = T{:,3};

    [Fmax, idx_max] = max(force);
    S0 = displacement(idx_max);
    Smax = displacement(find(force > 0, 1, 'last'));

    S0_plus_30 = S0 + 0.3 * (Smax - S0);
    Smax_minus_15 = Smax - 0.15 * (Smax - S0);
    eval_idx = displacement >= S0_plus_30 & displacement <= Smax_minus_15;
    F_eval = force(eval_idx);
end
```

```

    Fm = mean(F_eval);

    [F1, ~] = max(F_eval);
    [F2, ~] = min(F_eval);

    % Save for result matrix: [F1, F2, Fm, Fmax]
    BL_results(i, :) = [F1, F2, Fm, Fmax];
end

%Display result
disp('BL_results = [F1, F2, Fm, Fmax] for each test:');
disp(BL_results);

```