TEN CATE ADVANCED COMPOSITES BV
Subsidiary of Royal Ten Cate nv

Research & Development

Report ITD 9006-2A.01

Issue no.: 1
Issue date: 29-01-2015

Composite – Metal connections

for the automotive industry

Marco van Oosten
s1005774

Copies:

1 Archive (TCAC)

1 Library (TCAC)

Prepared:	Checked:	Approved:
(xx)	(xx)	

Table of contents

1. Introduction

Nowadays, many products and parts are produced using fibre reinforced materials. Especially in the aerospace and aviation industry, where weight reduction is important, more and more metal parts are replaced by lightweight composite parts. The goal is to reduce the total weight of the aircraft, which in turn reduces the fuel consumption. The automotive industry could also benefit from this, as the rules on gas emissions are getting stricter.

The applications of composite parts are however not often used in the automotive industry, as the material itself is quite complex in comparison to steel. The material requires a completely different design approach, where the most favourable design is a part built out of one whole instead of connecting two separate parts. This way the fibres are continuous throughout the entire part, as interruptions of the fibres can cause reductions in strength. It is therefore difficult to completely switch the material of an existing product with composite materials.

A small step in the direction of reducing weight of cars is a hybrid construction, where parts are created using a combination of composites and metals. Many parts can be produced in this way to reduce the weight of cars. An example of a part is the front-end, located at the front of a car where the lights and parts for cooling are connected to, which is already built in a hybrid form by some manufacturers [1, 2]. The technique can also be used to produce other parts, or even be used as an integration into the chassis of the car to improve the stiffness and strength. The goal of the hybrid structure is to use the best properties of both materials to create a stronger and lighter vehicle.

Metal and composites have to be joined together to realise these hybrid constructions. There are several methods available to do this like for example, adhesion, welding or mechanical connections. However, each method has there advantages and disadvantages and cannot be used in each application. This report will look into the different techniques, that are currently available, in joining composite material with metals. However, the majority of this report will only cover the adhesive connections, because researching and testing all methods would take too much time.

2. Materials

The first part will be to determine which materials will be joined together, as there are many different kinds of composites and metals. Materials are chosen based on the application of the hybrid connections. The general interest is for the automotive industry, the chosen materials should therefore be interesting for usage in this industry.

2.1 Metal

The most used metals in the automotive industry are steel and aluminium. The metals used for this research will therefore be limited to steel and aluminium.

2.2 Composite

Thermoplastic composites will be chosen to bond with the steel and aluminium. Costs of the material are the most important factor for choosing the composite material. Glass fibre reinforced polyamide and glass fibre reinforced polypropylene are two types of composites that are low in production costs and both materials have a good strength and are also chemical resistant which makes them good candidates for hybrid connections. There is however a downside of polyamide glass composites which is that polyamide (PA) absorbs moisture, which can affect the mechanical properties of this material.

3. Connection methods

There are a few methods available to join composites with metals. They can be divided into three different types, adhesives, welding en mechanical connections. All three methods work in different ways and not every method will be suitable for each application where composites will be bonded to metals. Each method will also require their own different pre-treatment, from surface modification to drilling of holes.

The most important factor is that the joining method can be applied in a fully automated production process. This means that time is a limiting factor for each process, as the slowest process will define the cycle time in the production process. The connecting of composite to metal will therefore have to be a quick process.

3.1 Adhesives

Quite a lot research has been done on joining composites to steel with the use of adhesives [2, 3, 4]. Most of it has been done using composites with an epoxy matrix[3]. This research cannot be applied to thermoplastic composites, as they are a completely different material and will react in a different way. There is also some research about adhering thermoplastic based composites to metals [2, 4], where most of the research is also based on the automotive industry. Figure 1 shows on of the front-ends that is realised during this research.

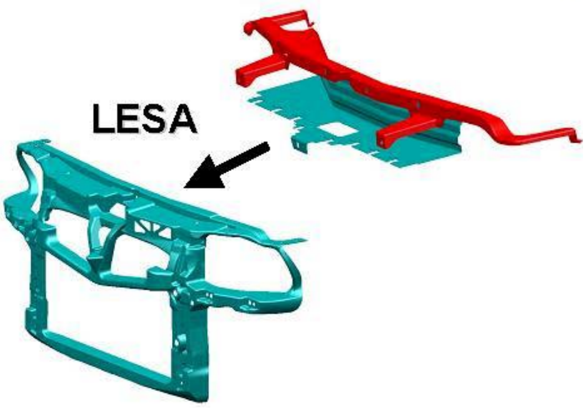


Figure 1: Composite-steel built using adhesives [2]

Glass reinforced PA and PP also are two of the most used thermoplastics in these researches, which are also the materials chosen for this report. A downside of PP is that the material has a low surface energy. This makes it almost impossible to wet the surface of this material with an adhesive. Pre-treatments or the use of primers can however increase the bonding strength. Also special type of low energy substrate adhesives have been developed especially for these type of materials. PA has the downside of absorbing moisture, which could not only affect its mechanical properties but also affect its adhering properties.

The adhering of composites to metal can be realised using a direct adhesive or by the use of a film, which connects both materials by melting [4, 5]. The use of a film will require a heating process, where both materials and the film are heated up to around 170-190 °C. This connection takes around two minutes to be realised, which is, despite the heating and cooling process, a quick process. This process will however heat up the entire product, which can become difficult with large product where only small areas are connected. Localising this heating process will make it look more like a welding process.

Direct adhesion will be much better approach in adhering both materials, which is also the method that is currently applied to the front-end of the VW Polo [2]. A special adhesive is used in this case, which is suitable for direct adhesion with polypropylene. A good adhesive needs to be found to realise a strong and fast adhesive connection between metal and composite. Surface treatments can also be used to initiate or strengthen the bond between composites and metals and they can be applied when necessary.

3.2 Welding

The welding of metals is a widely used production process. Composites however, cannot be welded with the same welding methods as used on metals. In order to weld composites, the polymer matrix has to be melted. This can be done by, for example, using a laser [6], induction [7] or ultrasonic welding [8].

A research on ultrasonic welding of metals to glass fibre reinforced polyamide was also recently performed by S. Bolt [8]. This process requires a polyamide film to be attached to the metal substrates, which will be used to adhere the fibre reinforced polyamide using ultrasonic welding.

Another welding method that is available is the cold-metal-transfer process. This process makes it possible to weld small spikes onto metal surfaces [9, 10]. These spikes build up fixation for dry laminate, which can be stacked on to them. There is little destructive damage to the fibres. The resin is infused to act as the adhesive which bonds the fibres to the metal [11]. A similar process to CMT is a so called Comeld^{TM} [10] joint, Figure 2, which works with the same principal of adding material to the metal to which the composite will attach.

Figure 2: Comeld joint

3.3 Mechanical connections

Mechanical connections are connections where bolts, screws or rivets are applied to join two materials together. These connection methods require holes to be drilled in both materials, which requires extra production steps. This not only costs extra time, it also weakens the materials. This will have a negative effects on the composite materials. Peak stresses will occur at these holes when load is applied, which can cause tear forming. This needs to be taken into account when using this connection method.

Another thing which needs to be taken into account is the appearance of this connection, as it is always possible to spot this type of connection, which is not desirable in every location of a car. The materials required for this connection are widely available, making it a cheap and simple connection despite the extra production steps. There also are fasteners specially developed for connecting composites, Figure 3 shows a picture of a fastener developed by NASA [12]. Fasteners like this could also be developed for joining composites and metals.

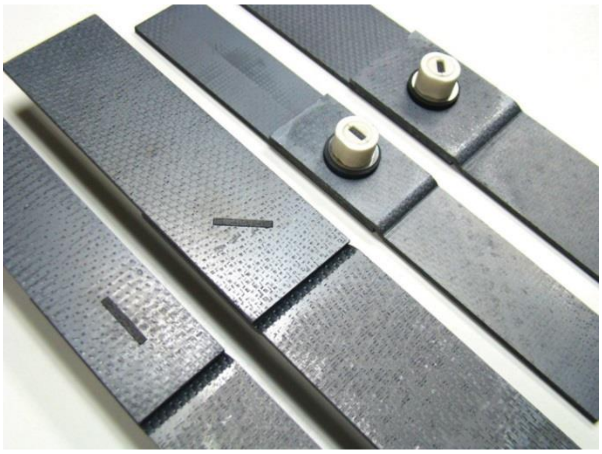


Figure 3: Composite fasteners developed by NASA [12]

4. Selection matrix

Each method of joining has its advantages and disadvantages. Therefore not every method can be applied, or is ideal, for every application. Appearance in an important factor, especially for cars. The outside of a car has to have a smooth surface, usage of mechanical connections will interrupt this smooth surface. This could be covered up, but requires additional process steps which are not desirable. There are a few other factors which are also important in the production process of joining metals to composites:

- Producibility
- Production time
- Mechanical properties
- Appearance
- Costs

Each joining method is producible, as each method has already been applied in numerous cases. The production time for each process will be different, welding requires little time as heat is induced at a rapid rate, but pre-treatment of the surface could require more time. Adhesion requires time for the adhesive to cure and also time for the surface to be treated. Mechanical connections require holes to be drilled, and rivets or bolts to be attached. The mechanical properties will be good with every method, however mechanical connections can encounter peak stresses at the edges of the holes, which need to be taken into account. The appearance at the surfaces will be the best when adhesives are used, as welding could leave a visible spot and bolts or rivets are easily spotted. Finally the costs will have a huge influence on the chosen method. These costs will include the investment and maintenance of the equipment that is required and production costs per product. Table 1 gives an indication on how each method scores on each factor, where more dots are more favourable.

Method	Producibility	Time	Mechanical properties	Appearance	Costs
Adhesion	•••	••	•••	•••	•••
Welding	•••	•••	•••	••	••
Mechanical connection	•••	••	••	•	••

Table 1: Joining method selection matrix

Adhesives show a good potential for connecting metals to composites and are therefore chosen as the main focus of this report. The other connection methods will not be discussed any further, because researching all connection methods would take too much time.

5. Adhesives

There are many different types of adhesives, each with their own advantages and disadvantages [13]. The next part of this report will look into these different types of adhesives and look at their application possibilities and most importantly, the curing speed, as this will define the cycle time of the automated production line.

5.1 Different types of adhesives

There are several different types of adhesives currently available on the market, each with their own properties. The most commonly used adhesives, are:

- Acrylic
- Cyanoacrylate
- Methacrylate
- Epoxy
- Polyurethane

5.1.1 Acrylic

Acrylic adhesives are flexible and tough adhesives which cure fast at room temperature. They consist out of two parts, the resin and an accelerator. Curing of the adhesive can be done by mixing both parts, or both parts can be applied separately to a surface and be put together to initiate the bonding. Upon closing, the adhesive spreads over the initiator and absorbs it. This method is effective for a small gap between both surfaces. To fill large gaps, the adhesive will have to be pre-mixed. Acrylic adhesives are generally used for fast assembly of small and medium sized components. Not all variants of acrylic adhesives are resistant to outdoor environment.

The benefits of acrylic adhesives is that the mixing does not have to be precise. The adhesive is also capable of bonding with poorly prepared surfaces but pre-treatments can improve the bonding strength.

5.1.2 Cyanoacrylate

Cyanoacrylate adhesives, also known as super glues, are easy to apply and have an extremely fast curing rate. They are however rather brittle which can result in lower strength. Also their impact resistance is quite low. Cyanoacrylate adhesives are normally developed for relative small surfaces and not all grades are suitable for outdoor applications, as they are usually poor in resistance to water and solvents. However, there are grades available which are applicable to larger surfaces and have a better resistance to environmental effects.

Their fast curing time would make them ideal for the automotive industry. However, the chosen cyanoacrylate will also require a good resistance against the environment.

5.1.3 Methacrylate
Methacrylate adhesives provide a good balance of high tensile, shear and peel strengths and a good impact resistance. These adhesives are capable of creating a strong bond. Just like acrylic adhesives, methacrylate also require minimal surface preparation. Methacrylate's are also tolerant to off ratio mixing and are also resistant to outdoor environment as they are water and solvent resistant.

The time to cure a methacrylate adhesives is relatively fast. Together with its strength and resistance against environmental effects, it can create strong and durable bonds.

5.1.4 Epoxy
Epoxy adhesives are the most widely used structural adhesive. They are a thermosetting resins which solidify by polymerisation. Epoxies usually consist out of two parts, a resin and a hardener. There are however also epoxies which consist out of one part, that solidifies at elevated temperatures. Epoxy adhesives offer high shear strengths and fill up small gaps with little shrinkage and have a good resistance against environmental effects.

The cure rate of epoxies is generally slow, but can be increased by heating the adhesive. A pre-treatment of the surface is necessary to remove any grease or oils.

5.1.5 Polyurethane
Polyurethane adhesives are tough adhesives, which stay flexible even at low temperatures. They have fairly good shear strength but have a weak water and humidity resistance, this can however be reduced by applying a primer onto the adhesive after it is cured . They are relatively inexpensive and have excellent gap filling properties, but also have a long curing time.

6. Adhesive choice
Choosing the best adhesive for a fully automated production line depends on a number of factors. The most important factors are the curing time, bonding strength and the resistance to environmental effects. The adhesives bonding properties with PA, PP, steel and aluminium are important to know in order to make a choice between the different types of adhesives. Datasheets from adhesive manufacturers provide information about what type of adhesive will bond with PA or PP [14, 15, 16]. The first criteria for choosing an adhesive is that it can create a proper bond between PA or PP and the chosen metals. Strength of the adhesive will be a concern after they are chosen and a testing method is determined.

Table 2 shows how well each type of adhesive will bond with the materials that are used, one dot indicates that bonding is possible, two will most likely give a good bond and three dots will give a strong bond. The bonding is however strongly dependent on the grade of the adhesive that is used, as the adhesive properties can differ with different grades of each type of adhesive.

Adhesive	PA	PP	Steel	Aluminium
Cyanoacrylate	•••	••• (with surface treatment)	••	••
Methacrylate	••	•• (with surface treatment)	•••	•••
Acrylic	••	••	••	••
Epoxy	•	-	•••	•••
Polyurethane	••	-	••	••

Table 2: Bonding possibility

Table 3 shows the properties of each adhesive. The curing time, more dots is faster, and the resistance to environmental effects, more dots is better, are shown here. Each adhesive will be capable of creating a strong bond, this is therefore not compared.

Type of adhesive	Curing time	Environment resistance
Acrylic	••	•••
Cyanoacrylate	•••	••
Methacrylate	••	•••
Epoxy	•	•••
Polyurethane	•	••• (with coating)

Table 3: Properties of different adhesives

It is now possible to eliminate a few types of adhesives which do not fulfil the requirements. Epoxies give a good bonding to metals, but do not to bond well to the two polymers that are used. Epoxies also requires a long curing time which makes them unsuitable for this application. Polyurethane adhesives also require a long curing time, which makes them also unsuitable.

This only leaves three possible adhesives that have a chance to be used for metal and composite connections. The next step is to find the right adhesive that will bond well to both polymer and metal and has a fast enough curing time.

Certain grades of acrylic based adhesives can bond well with both PA and PP. The bond can be strengthened by giving the materials a surface treatment. The only downside is the curing speed of this type of adhesive, which is slower than the curing speed of the other two types of adhesive.

Cyanoacrylates have a fast curing rate, usually within minutes. This makes them ideal for usage in a fully automated production line. They should produce good bonds with both polymers and the metals, but there are two factors which need to be taken into account. These are, the resistance to environmental effects and the impact resistance, as cyanoacrylate's can be rather brittle.

Methacrylate adhesives will require a surface treatment before proper bonding with PP, which will involve an extra step in the production process. This is however not a problem if the adhesive can produce high strength bonds.

6.1 Chosen adhesives

Now a choice of adhesive can be made from looking at manufacturers data sheets of acrylic, cyanoacrylates and methacrylate adhesives. The main focus of adhesive choice here is that the adhesive can produce a good and fast curing bond with either PA or PP and the chosen metals. The following adhesives were chosen based on these criteria and are stated in Table 4.

Name	Manufacturer	Type of adhesive
Araldite® 2021 [17]	Huntsman advanced materials	Methacrylate
Loctite® 4090 [18]	Henkel	Cyanoacrylate/epoxy hybrid
Scotch-Weld™ DP-8005 [19]	3M	Methacrylate
Cyanoacrylate 1500 V-AM-15 [20]	Ruplo lijmtechniek	Cyanoacrylate
Cyanoacrylate 1500 V-AM-15-1 [20]	Ruplo lijmtechniek	Cyanoacrylate

Table 4: Chosen adhesives

The difference between cyanoacrylate 1500 V-AM-15 and cyanoacrylate 1500 V-AM-15-1 is that cyanoacrylate 1500 V-AM-15-1 contains 5% of rubber, which should enhances its impact resistance but will also reduce its strength. The adhesive is also available with a larger content of rubber, which could be used depending on the requirements of the application.

7. Surface treatment

To achieve a good bond, it is important that the surfaces of both joining components are in good condition for the adhesive to adhere to it. There are a few general conditions that the surface needs to fulfil in order to get a good bonding. It has to be clean, dry, dust free, smooth, non-porous and wettable (high surface energy) [21]. This is however not the case with polypropylene, which has a very low surface energy making it a difficult to adhere surface. There are adhesives specially made for this type of materials which were successfully tested [22], but there also are surface treatments to increase the surface energy and create a better bond. Surface treatments which can be applied to the composite parts are:

- Abrasion/solvent cleaning
- Grit blasting
- Primer
- Acid etching
- Corona treatment
- Plasma treatment
- Flame treatment

7.1 Abrasion/solvent cleaning

In this treatment, the surface is abraded with abrasive paper and cleaned afterwards to remove all particles, grease and mould release agents from the material [23]. This method has been tested on both thermoset and thermoplastic materials. An increase in bonding strength was found for thermoset materials when this treatment was used [24]. However, this is not always the case for thermoplastic materials. Research showed that in some cases the bonding strength will be equal or lower compared to the non-abraded surface [23, 24]. The treatment did not work for the adhesives that were used during this research, but this does not mean that they do not work for other adhesives.

7.2 Grit blasting

Grit blasting is a treatment where alumina grit or glass beads are blasted at the surface, Figure 4 shows a grit blast treatment [25]. This is followed by a solvent rinse [23]. This method gave the same results as the abrasion/solvent cleaning treatment. The bonding strength for thermoset materials increased, but the bonding strength for thermoplastics did not increase much [23].

Figure 4: Grit blasting [25]

7.3 Primer

Primers can be used to increase the surface energy of PP. These primers are widely available and have proven to make it possible to bond PP with certain types of adhesives which otherwise would not bond. They are mostly provided by the adhesive manufacturer for an optimal result with their adhesive, but not every manufacturer produces these primers. Using a primer, that is not provided by the manufacturer, will require testing in order to find out if they work with the adhesive.

7.4 Acid etching

Chromic acid solutions can be used to etch the surface of polyolefins, the group of polymers with have a very low surface energy, and increase their surface energy [26]. Etching has proven to increase the peel strength of PP by 170 times the strength of an untreated surface just after 60 seconds, see Figure 5. The peel strength quickly reaches its maximum after 200 seconds. This procedure can increase the peel strength of adhesive bonds and is a method that could be applied in joining composites to metals. It is a fairly simple method which only requires a chromic acid solution. However, chromic acid is carcinogen and harmful. Caution is required when using this pre-treatment.

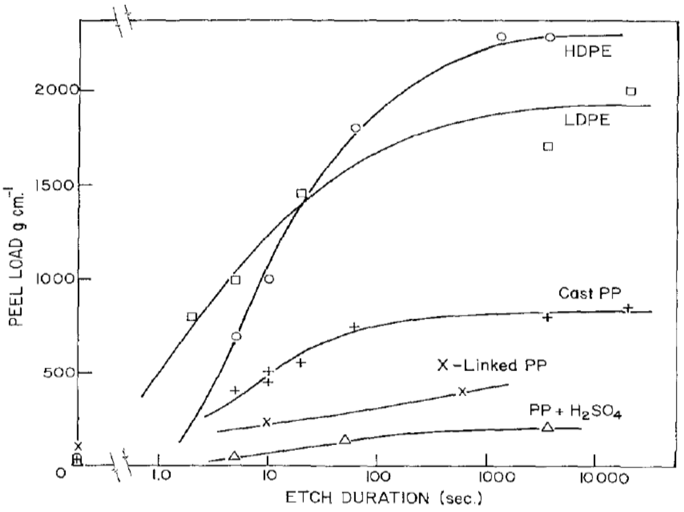


Figure 5: Peel strength vs etching duration [26]

7.5 Corona treatment

Corona-discharge treatment [24] is one of the most used pre-treatment for polyolefin materials. This technique uses a metal electrode, covered by an insulator, which floats one to two mm above the surface of the polyolefin. High voltage is applied to the electrode and increased until the air gap is ionized, creating a plasma at atmospheric pressure. Results have revealed that the corona treatment increases surface tension and can alters the surface chemistry by oxidising the polymer matrix, which will result in an increased bonding strength [27]. The corona treatment is a treatment that can be used to increase the strength of composite to metal bonds, Figure 6 shows a corona treatment on a plastic part.

Figure 6: Corona treatment [28]

7.6 Plasma treatment

Plasma treatment involves a low-pressure plasma gas, which is electrically conductive. This process can have multiple reactions on the polymer surface, it can clean, etched or chemically modify the surface [23]. The combination of these processes results in an improvement of the adhesion properties of the surface. Plasma treatments have been proven to enhance the surface tension, oxidise the polymer matrix and increase the bond strength of PEEK composites [29]. It can also be applied on PP to increase its surface energy to allow for better bonds.

7.7 Flame treatment

Flame treatment is also widely used to modify the surface of polyolefins, usually to improve printability and paint ability. The flame is used to oxidise the surface to increase the surface energy. This is ideal for use on PP to create, or improve the bonding between composites and metals. Figure 7 shows how the flame treatment looks like.

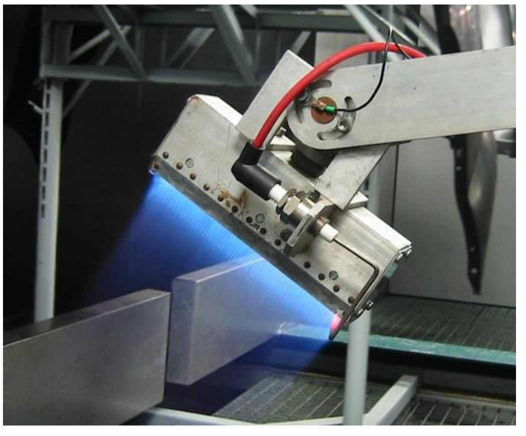


Figure 7: Flame treatment [30]

7.8 Without surface treatment

There are certain adhesives available which do not require any pre-treatment. Guedes Pinto et al. [22] researched two types of this adhesive and concluded that these adhesives can produce good, strong bonds between two pieces of PP material. They also concluded that strength of the bond lowered when the surfaces were abraded using sanding paper, which is also not recommended by the manufacturer to do so. However, most adhesives will require a pre-treatment before bonding to PP is possible.

7.9 Metal surface treatment

Treatments for metals are also important because of the surface oxidation of steel and aluminium [31]. Initial bonds can be good, but they could degrade rapidly under environmental exposure because of oxidation. Etching procedures are not recommended for steel. The best methods for pre-treating steel are abrasion and grit blasting. Also the appliance of a protective layer, like galvanising, can increase the bonding strength [5] and increase protection against the environment.

For aluminium it is possible to etch the surface to increase bonding strength, but also abrasion or grit blasting is often used to increase the bonding strength. Etching with nitric acid has proved to increase the bonding of aluminium [8] and could be a good treatment to improve the bonding of the adhesives to aluminium.

7.10 Possible treatments

Table 5 shows how the treatments affect the bonding strength. A plus indicates an expected increase and an minus indicates that there is no increase in strength.

Treatment	Composite	Steel	Aluminium
Abrasion/solvent cleaning	-/+	+	+
Grit blasting	-/+	+	+
Acid etching	+	-	+
Corona treatment	+		
Plasma treatment	+		
Flame treatment	+		
Galvanising		+	

Table 5: Surface treatments for composites

For composites, acid etching, corona, plasma or flame treatment can be applied to improve the strength of the adhesive. Steel could be abraded, grid blasted or galvanised in order to strengthen the bond and aluminium can be abraded, grit blasted or etched. Each adhesive manufacturer will state the surface treatments that are necessary for proper bonding, with the adhesives they supply. Additional surface treatments can be applied depending on the results of the tests with the standard surface treatment, advised by the adhesive manufacturer.

8. Experiments

The bonding between composite and metal can be evaluated in many different ways. The simplest method, which should give a good estimation on what the adhesive's strength is, is the single lap shear test. The single lap shear test is also easy to perform and is therefore chosen to characterise the adhesives. The standard for a single lap shear test, between composite and metal, is ASTM D5868-01 [32]. All specimens will be tested according to this standard.

The lap shear tests will not include additional surface treatments other than the treatments recommended by the manufacturers. Three different sets of lap shear tests will be performed with each adhesive. One test will be done using glass PP and the other two test will be performed using glass PA, where one set uses PA that is untreated and the other uses PA that is dried in an oven, 168 hours at 85°C. This is done to remove moisture from the PA, because PA absorbs moisture which could affect the bonding strength. The difference between untreated and dried PA can be evaluated by doing two tests on PA. These three lap shear test will be performed on steel and aluminium, which gives a total of six different lap shear tests for the five chosen adhesives.

The oven dried samples of glass-PA are kept in a sealed glass bowl with moisture absorbing granules. This way, the moisture content of the glass-PA is kept as low as possible after they have been removed from the oven. However, the sample have to be removed from the bowl to be adhered and for measuring. The samples spend a total time of 2 hours outside of the bowl before adhering to the metal. After they have been adhered to the metal parts, they will not be placed inside the bowl again.

Another requirement is set for the adhesive to fulfil, based on the chosen testing method. The adhesive should be able to produce a structural bond, this way the connection could also be used for a structural application. A structural adhesive is defined by its minimal laps shear strength, which should at least be 1000 psi (6.9 MPa), according to 3M adhesives [16]. The goal will be to find a structural adhesive for all combinations of metals and composites.

8.1 Lap shear test

Figure 8 shows the dimensions of the substrates, prescribed by the ASTM standard, which should be around 100 mm long and 25 mm wide. The thickness is also fixed, at 1.5 mm for the metal part and 2.5 mm for composite part. A small deviation was made from this standard, 2 mm composite material was used. This was done because the 2.5 mm composite was not in stock.

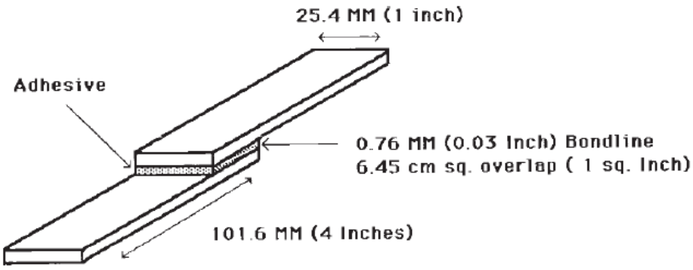


Figure 8: Lap shear model [32]

Also the thickness of the adhesive bond is set by the standard, which should be 0.76 mm thick. This is however too thick for all of the chosen adhesives, which require a bonding thickness from 0.1 mm to 0.2 mm for optimal strength, depending on each adhesive. The thickness advised by the manufacturer, which are stated in Table 6, will be used during the lap shear tests, as this will most likely give the best results.

Adhesive	Advised thickness
Araldite® 2021	0.05 – 0.1 mm
Loctite® 4090	Not specified
Scotch-Weld™ DP-8005	0.12 – 0.2
Cyanoacrylate 1500 V-AM-15	0.1 – 0.2
Cyanoacrylate 1500 V-AM-15-1	0.1 – 0.2

Table 6: Optimal adhesive thickness

The lap shear test according to Figure 8 is difficult to realise on a tensile tester, as the grips are perpendicular to each other and cannot be moved. Two tabs will need to be added to the setup in order to make it possible to perform the lap shear tests on a standard tensile tester. Figure 9 shows how the setup will look like with the tabs in place. The tabs are also adhered to the substrates, which will be done using the same adhesive that is used for the overlap. The overlap of the bond will be 25 mm, which gives a total bonding area of 625 mm². Glass tabs of 1.5 mm thick are used to adhere to the composite and glass-PA tabs, 2 mm thick, will be used to adhere to the metal.

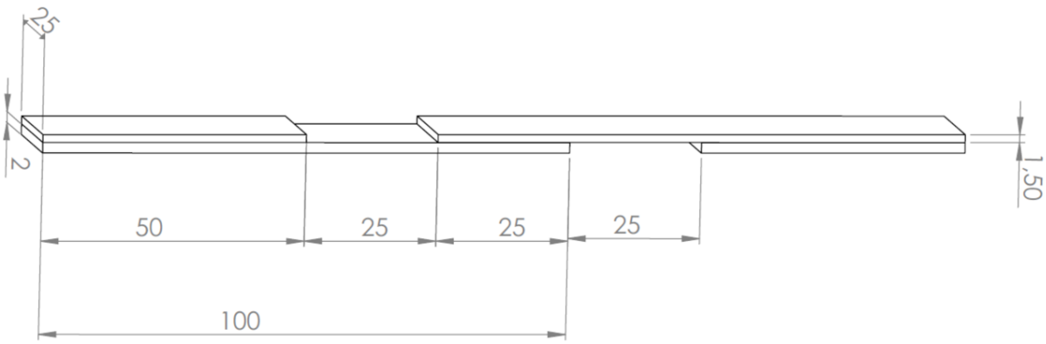


Figure 9: Lap shear test setup

Eight specimens will be made for each lap shear test to accurately determine the lap shear strength of each connection. Six of them will be tested and the other two are backup and will only be tested if the first six specimen give a large deviation in shear stress or if a specimen breaks, prior to the testing. The initial grip separation length will be 75 mm and the loading rate will be 13 mm/min as stated in the ASTM standard [32].

The thickness and width of all substrates are measured prior to the bonding. Each substrate is measured in three places and the average width and thickness are taken. After the bonding of two substrates, they will be measured again. This time the thickness and the overlap length will be measured. The thickness is measured to find out how thick each adhesive layer is, this is also measured on three points of the overlap. The overlap length is measured on each side of the adhesive layer. The surface of the adhesive bond is equal to the smallest width, of the two substrates, multiplied by the average overlap length. The shear stress will be calculated by dividing the force with the area of the adhesive bond.

8.2 Failure modes

There are a few possibilities in which the adhesive layer can fail. These failures are classified in three different failure modes, which can occur during the lap shear tests, cohesive failure, adhesives failure and structural failure. These three failure modes are shown in Figure 10. Cohesive failure (CF) is the failure of the adhesive itself, leaving residue on both of the substrates. Adhesive failure (AF) is the failure of the adhesion to one of the substrates and structural failure will be the failure of one of the substrates, where material is torn off from the surface of one of the substrates (SF). It is also possible to see a combination of these three failure modes.

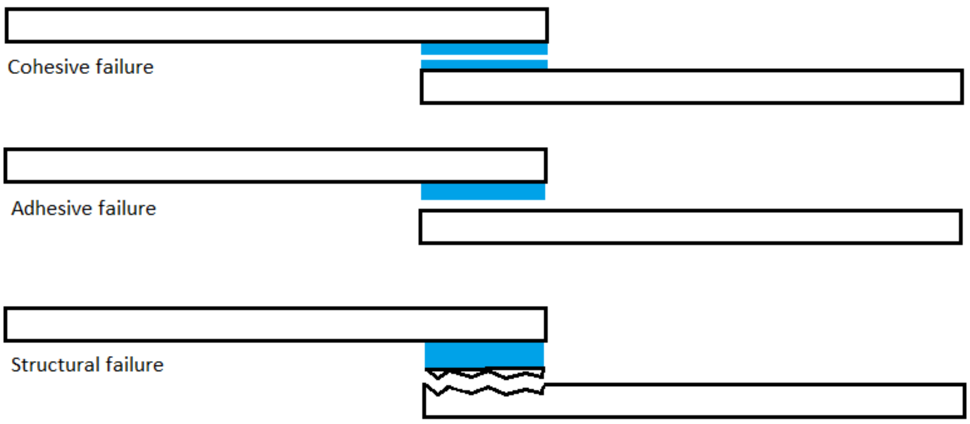


Figure 10: Failure types

8.3 Surface treatments

Some surface preparations are required for each of the chosen adhesives. The treatments, which have been recommended by the manufacturer, are shown in Table 7. For the metals, each treatment will be the same. This treatment will be abrasion of the surface, with sanding paper 180, and degreasing, which is done using isopropanol. The treatment for PP and PA vary for each of the adhesives.

Adhesive	Glass-PA	Glass-PP
Araldite® 2021	Abrading and degreasing of the surface	Abrading ,degreasing of the surface and applying a primer*
Loctite® 4090	Abrading and degreasing of the surface	Degreasing and applying a primer*
Scotch-Weld™ DP-8005	Abrading and degreasing of the surface	Degreasing
Cyanoacrylate 1500 V-AM-15	Abrading ,degreasing of the surface and applying a primer**	Abrading ,degreasing of the surface and applying a primer**
Cyanoacrylate 1500 V-AM-15-1	Abrading ,degreasing of the surface and applying a primer**	Abrading ,degreasing of the surface and applying a primer**
*** Loctite 770**		
**** Primer PE/PP (Ruplo lijmtechniek)**		

Table 7: Surface preparation according to the manufacturer

The PE/PP primer, manufactured by Ruplo Lijmtechniek, comes in different variants. Three of these variants are, PE/PP-S, PE/PP-10 and PE/PP-20. Each primer has a different speed in which it reacts with the adhesive. PE/PP-S reacts very fast and is more suitable for connecting two polymers to each other. This however, could reacts too fast for a proper adhesion to steel, a small test using Cyanoacrylate 1500 V-AM-15-1 and the different primers was done on a glass-PP and steel connection to see which primer works best.

Figure 11 shows how each combination of adhesive and primer fails when the glass-PP part is peeled off of the steel part. PE/PP-S and PE/PP-20 show both a combined failure mode of adhesion on to the steel and structural failure of the glass-PP. PE/PP-10 shows an almost complete structural failure of the glass-PP part. PE/PP-10 will most likely give the best results for bonding steel to composite and will therefore be applied on the connection of composite to metal.

Figure 11: Failure mode of glass-PP to steel using Cyanoacrylate 1500 V-AM-15-1

8.4 Bonding test

The adhesives will require some bonding test prior to the lap shear tests to see if the adhesive adheres to the materials. This is done by adhering the tabs to the substrates and checking how well the bonding between tab and substrate is. This can determine which combination of adhesive and materials can be used for testing and which combinations could require additional surface treatments to initiate the bonding. Table 8 shows how well each adhesive bonds with the materials. The adhesives were tested by flexing a substrate. Good means that the adhesive survived the flex without any visible or audible damage, moderate bonds break down when flexed by hand and bad bonds break immediately when slightly flexed.

Adhesive	PA	PP	Steel	Aluminium
Araldite® 2021	Moderate	Bad* Bad**	Good	Good
Loctite® 4090	Good	Good*	Good	Good
Scotch-Weld™ DP-8005	Good	Good	Good	Good
Cyanoacrylate 1500 V-AM-15	Good**	Good**	Good	Moderate
Cyanoacrylate 1500 V-AM-15-1	Good**	Good**	Good	Moderate

*** with use of primer: Loctite 770**
**** with use of primer: Primer PE/PP-S (Ruplo lijmtechniek)**

Table 8: Bonding of each adhesive

Araldite 2021 could not adhere the glass tabs to the PP substrates, with use of the Loctite 770 primer. It failed in a purely adhesive failure mode, where the adhesive did not adhere to the PP, Figure 12. The pattern of the adhesive is still visible on the glass-PP, but there is no residue on the surface.

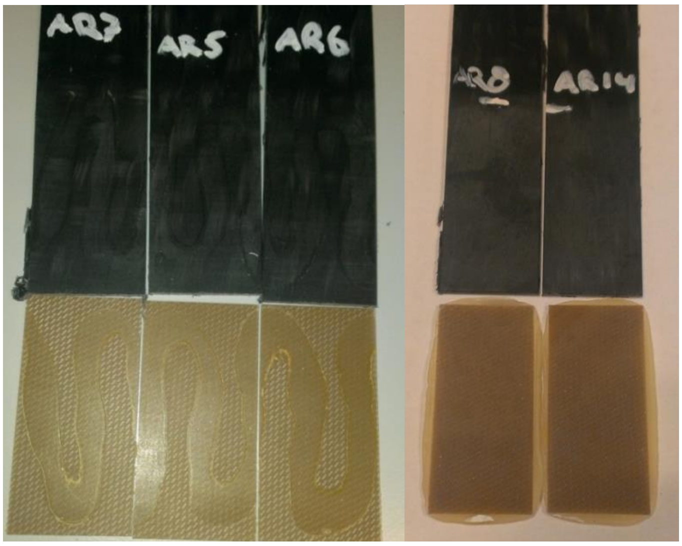


Figure 12: Adhesive failure of Araldite 2021 on Glass-PP with primer Loctite 770 (left) and PE/PP-S primer (right)

Another test was performed, with the araldite adhesive, using the PE/PP-S primer and also a bit more adhesive to fully cover the surface. This gave the same results as with the Loctite 770 primer, Figure 12. Knowing that both primers do work, means that araldite 2021 cannot be applied to PP with the use of these primers. It may be that there is a different primer available that will make the araldite bond to PP, but this is not investigated any further and araldite 2021 will only be used to adhere PA to the metal substrates.

8.5 Preparation

The next step towards the lap shear experiments is the preparation of the specimens. Ideally all substrates, metal and composite, and tabs should be adhered to each other before cutting them into the right size, this way all specimens would be aligned in the same way. It is however not possible to cut the combination of metal and composites with the available equipment. Therefore the metal parts are ordered according to the required size and each substrate is separately adhered to each other, which unfortunately makes it possible to have small misalignments. Each bond was kept in place, for at least one day, using two paper clamps which applied pressure to the bond. All adhesives acquire their full strength after one day of curing at room temperature (23 °C), and will be tested after one day of curing. The steel substrates that were ordered were however all slightly bended, which could have some effect on the lap shear strength.

8.6 Adhesive strength

Three of the chosen adhesives had an indication of maximum shear stress that could be achieved with a single lap shear test on a few of the chosen materials, their values are stated in Table 9. These values can be used to compare with the lap shear tests that will be performed on the composite-metal connections. It could be that the strengths will differ from these values because the two materials that are joint together are not the same, but this will become apparent from the results of the lap shear tests. Loctite 4090 gives a very low shear stress that could be achieved with PP, but it could be that this will improve with the use of a primer. The other two adhesives did not have any data sheets, so it will not be possible to compare them after testing.

Adhesive	PP (MPa)	PA (MPa)	Steel (MPa)	Aluminium (MPa)
Araldite® 2021 [17]	-	3	23	22
Loctite® 4090 [18]	0.6	-	17	7.6
Scotch-Weld™ DP-8005 [19]	7.58	-	17.24	15.68

Table 9: Lap shear strength according to the data sheets

9. Theory

There are a few theoretical models available which give an indication on how the stress distribution will look like throughout the adhesive layer during a single lap shear test. All models give a similar curve with stress peaks on both edges of the adhesive layer, where either substrate ends, and a stress which is a bit lower than the mean stress in the centre. One of these models will be used to see how the stress distribution will be when two completely different materials are used and to predict the stress distribution of the chosen adhesives in a connection to steel and aluminium. The model requires the Young's modulus of the materials that are joint. The differences in the Young's modulus of the composite materials, glass-PP and glass-PA, are very small and will therefore be chosen equally at 20 GPa.

9.1 Klein/Li model

The theoretical models that will be evaluate is the Klein/Li model [33]. This model is applied on a setup showed in Figure 13 and it uses three assumptions to simplify the problem:

- All cross-sections will remain constant
- The adhesive behaves in a linear elastic way
- There is no bending moment on the cross-section

The stress distribution will be calculated based on the displacement of the adhesive layer during loading. This will result in a stress distribution, $\tau(x)$, which is defined as followed:

$$\tau(x) = \frac{\omega \cdot \tau_m}{(\beta+2)(\cosh(w)-1)}(\sinh\left(\omega \cdot \left(1-\left(\frac{x}{l_ü}\right)\right)\right) + (\beta+1)\cdot \sinh\left(\omega \cdot \left(\frac{x}{l_ü}\right)\right))$$

Where ω and β are two constants, which depend on the material properties, the Young's modulus and thickness, and on the properties of the adhesive.

$$\omega = \lambda \cdot l_ü$$

$$\lambda^2 = \frac{E_1 \cdot t_1 + E_2 \cdot t_2}{E_1 \cdot t_1 \cdot E_2 \cdot t_2} \cdot \frac{G_{Kl}}{d}$$

$$\beta = \frac{(E_2 \cdot t_2 - E_1 \cdot t_1)\cdot G_{Kl} \cdot l_ü^2}{E_1 \cdot t_1 \cdot (G_{Kl} \cdot l_ü^2 + E_2 \cdot t_2 \cdot d)}$$

Figure 13 show the setup which the model is used for, where the shear stress goes from left to right through the adhesive layer.

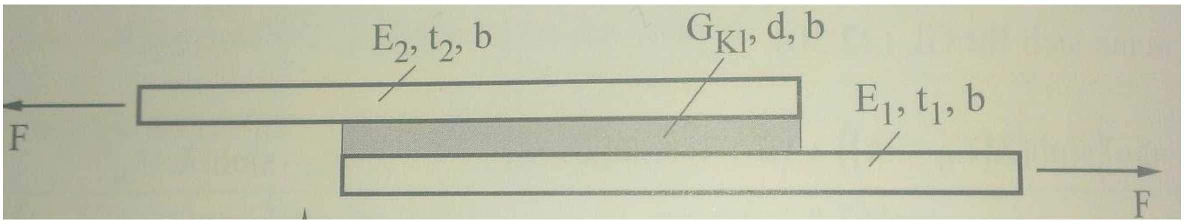


Figure 13: Lap shear setup [33]

Using the stress distribution with a mean stress, τ_m, of 1 MPa and the values stated in Table 10 gives a stress distribution which is shown in Figure 14. This shows that the maximum stress, during a lap shear test, will be at the point where either of the two materials stop. At these points the stress will be three times the average shear stress. This means that the adhesive layer is most likely to fail at one of these two points.

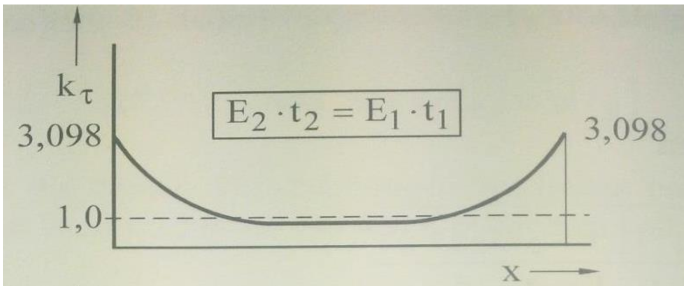


Figure 14: Stress distribution, lap shear, aluminium-aluminium [33]

E_1	t_1	E_2	t_2	G_{Kl}	d	$l_ü$
70 GPa	1.5 mm	70 GPa	1.5 mm	1 GPa	0.2 mm	20 mm

Table 10: Values used to in the stress distribution of Figure 14

The stress peaks will have an equal value on both ends of the substrates when the same material is used for both substrates. This is however not the case when two different materials are connected to each other. Figure 15 shows two stress distribution shifts, where one of the materials has either a Young's modulus or thickness which is twice as high or twice as low.

The maximum stress, in case of two different materials, will be higher on the side of the material with the lowest Young's modulus multiplied with the thickness. This means that the peak stresses will be higher during a lap shear test, which will lower the mean stress that the adhesive layer can handle. This effect is very important when combining glass fibre reinforced polymers and metals, as the fibre reinforced polymers have a much lower Young's modulus.

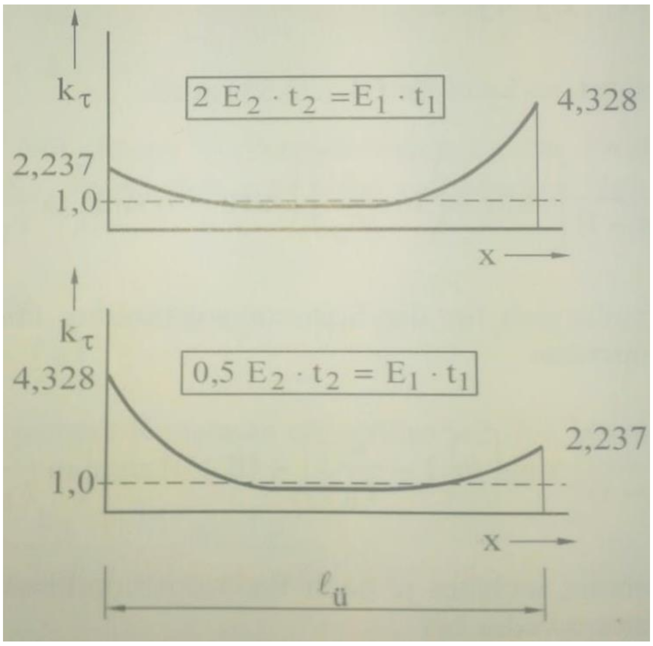


Figure 15: Stress distribution of different types of material [33]

Figure 16 and Figure 17 show how the stress distributions will be for the combination between composites and metals. The shear modulus and thickness of the adhesive are chosen the same as used for Figure 14 and Figure 15 to get an indication on how the stress distribution will be in comparison to these distributions.

Figure 16 shows how the stress will distribute throughout the adhesive layer when composites are connected to steel, using the values stated in Table 11. This shows that the difference between the two materials is so large, that the peak stress will be more than eight times as large as the mean stress. The same distribution is also modelled for the connection of composite and aluminium, Figure 17. This also shows that the stress peak is higher on the side of the composite. The peak stress will be more than seven times as large as the average stress, but the peak is only two and a half times as large as the peak on the side of the aluminium. The peak is a bit lower because the difference between the Young's moduli are smaller, compared to a composite-steel connection.

The high stress peaks, caused by the large difference in Young's modulus, can result in failure of the adhesive at a low mean shear stress.

E_1	t_1	E_2	t_2	G_{Kl}	d	$l_ü$
210 GPa	1.5 mm	20 GPa	2 mm	1 GPa	0.2 mm	25 mm

Table 11: Values used to in the stress distribution of Figure 16

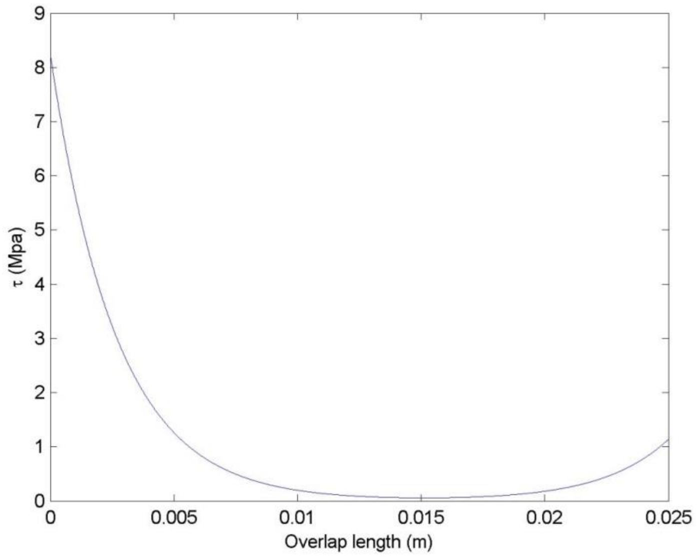


Figure 16: Stress distribution, lap shear, GFR PA-Steel

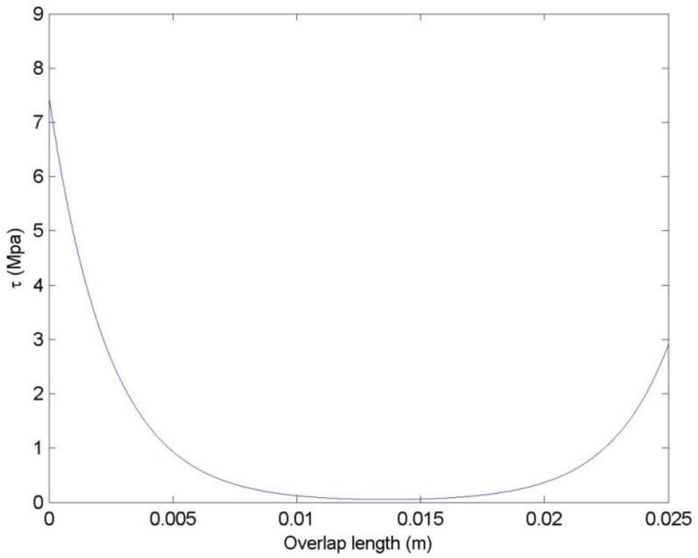


Figure 17: Stress distribution, lap shear, GFR PA-Aluminium

E_1	t_1	E_2	t_2	G_{Kl}	d	$l_ü$
70 GPa	1.5 mm	20 GPa	2 mm	1 GPa	0.2 mm	25 mm

Table 12: Values used to in the stress distribution of Figure 17

The peak stresses can be reduced by reducing the thickness of the substrates across the adhesive length. Figure 18 shows how the setup will look like when this is applied. The reduction of the thickness will give a more gradual guide the force through the adhesive, which will also lower the peak stresses. This is shown in Figure 19, where the same stress distribution is shown as in Figure 14 with and without reduction of the thickness.

This reduction of thickness does however not have the same effect when applied to the composite and metal connection. The peak will only slightly reduce, not more than a few per cent. This reduction is not significant enough to increase the average shear stress. The reason that this will not have any effect is most likely because of the large differences in Young’s moduli.

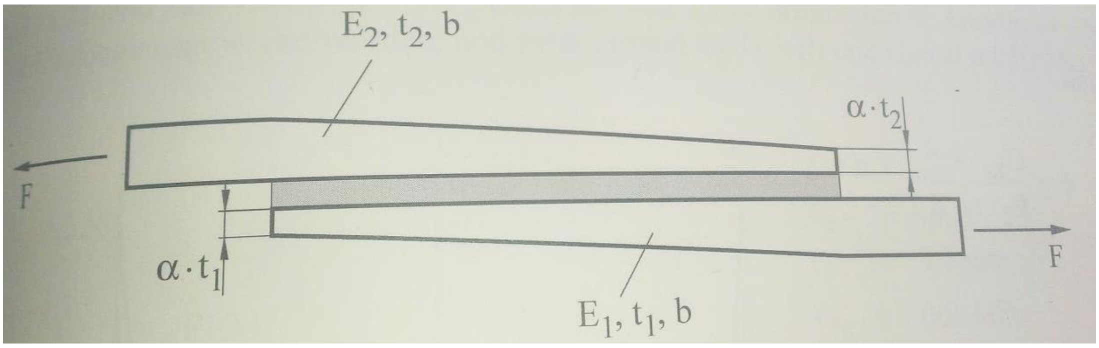


Figure 18: Layout with reduced thickness over the adhesive length

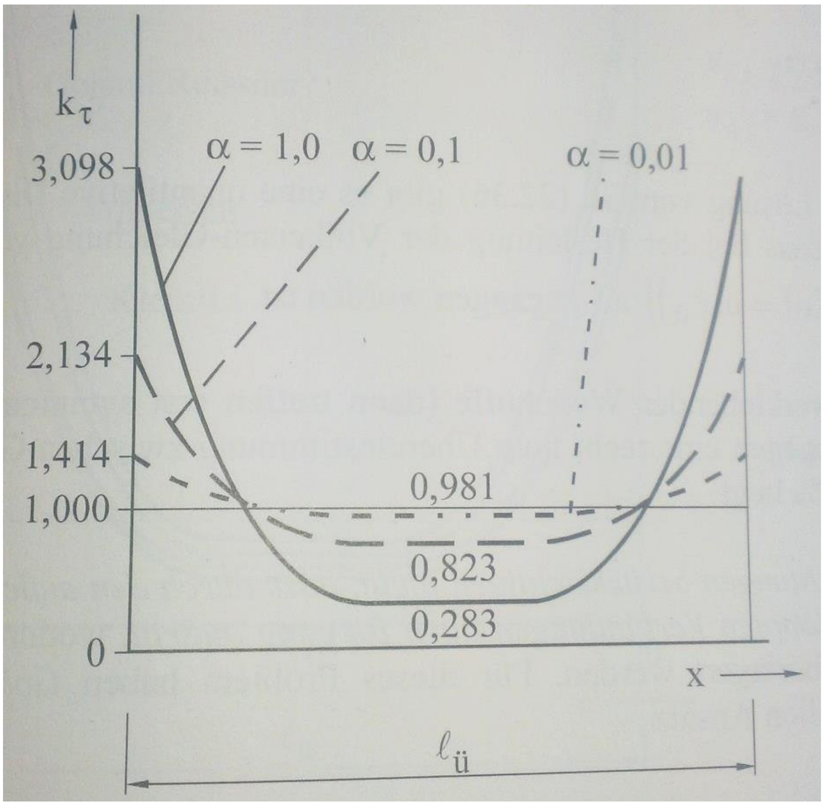


Figure 19: Stress distribution with reduced thickness

A different approach to lower the stress peaks will be to increase the thickness of the composite part. Figure 20 and Figure 21 show the stress distributions using a composite substrate which is twice as thick as the previously used substrate. This shows a reduction in stress peaks for both the aluminium and steel connection, and could be used to improve the strength of the connection. The same shift could also be achieved by reducing the thickness of the steel or aluminium part.

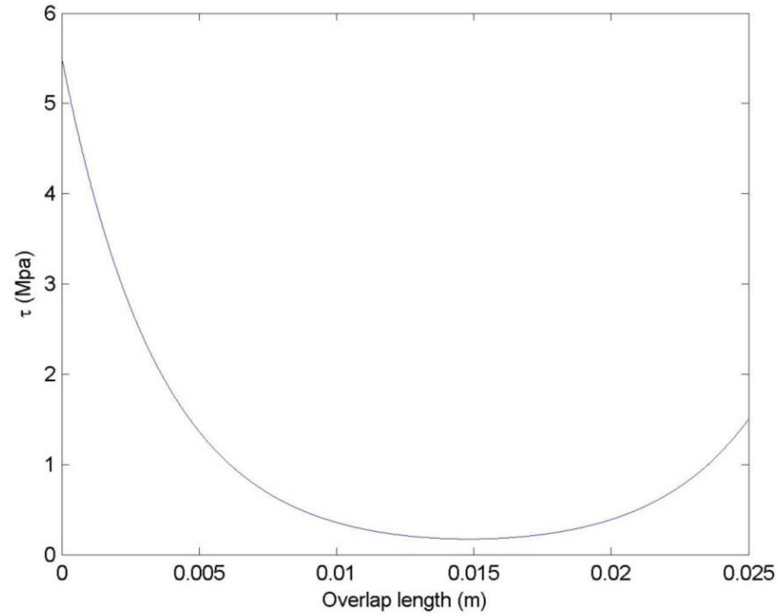


Figure 20: Stress distribution, lap shear, GFR PA-Steel

E_1	t_1	E_2	t_2	G_{Kl}	d	$l_ü$
210 GPa	1.5 mm	20 GPa	4 mm	1 GPa	0.2 mm	25 mm

Table 13: Values used to in the stress distribution of Figure 20

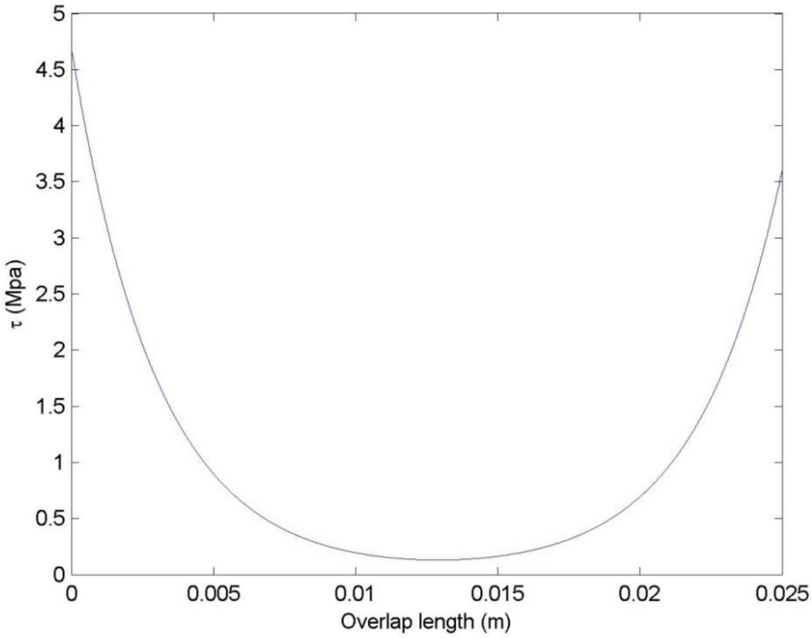


Figure 21: Stress distribution, lap shear, GFR PA-Aluminium

E_1	t_1	E_2	t_2	G_{Kl}	d	$l_ü$
70 GPa	1.5 mm	20 GPa	4 mm	1 GPa	0.2 mm	25 mm

Table 14: Values used to in the stress distribution of Figure 21

9.2 Stress distribution of the adhesives

Calculating the peaks which will, theoretically, be achieved with the specimens that were prepared is only possible if the shear modulus and the thickness of the adhesion are known. The shear modulus of the adhesives are not always provided by the manufacturers. Only the shear modulus of the DP-8005 was presented in the data sheet. The other shear moduli were estimated, based on general shear moduli of these types of adhesive [34], and are stated in Table 15, together with the optimal thicknesses of the adhesives. The thickness for Loctite 4090 was taken equal to the thickness of the cyanoacrylates, because the ideal thickness is not provided by the manufacturer.

Adhesive	G_{Kl} (GPa)	d (mm)
Araldite® 2021	1	0.1
Loctite® 4090	1	0.15
Scotch-Weld™ DP-8005	0.6 [20]	0.16
Cyanoacrylate 1500 V-AM-15	1	0.15
Cyanoacrylate 1500 V-AM-15-1	0.9	0.15

Table 15: Shear modulus and thickness of the adhesives

Figure 22 and Figure 23 show the stress distributions of the adhesive layers for composite to steel and composite to aluminium. Both curves have the same shape, but the combination of aluminium and composite gives a lower peak stress for every adhesive. However, the maximum shear stress that can be achieved with each adhesive will still depend on the strength of the adhesive itself. So these figures do not tell which adhesive will fail first. There are also some other factors which influence the strength of the adhesive, like outflow of the adhesive [35], which will have a positive effect on the strength, and the adhering property to the surface of the substrates. The model does not take into account that one substrate could have a stronger bond than the other, it just shows how the distribution of the stress will be. Also deformation of the substrates is not taken into account.

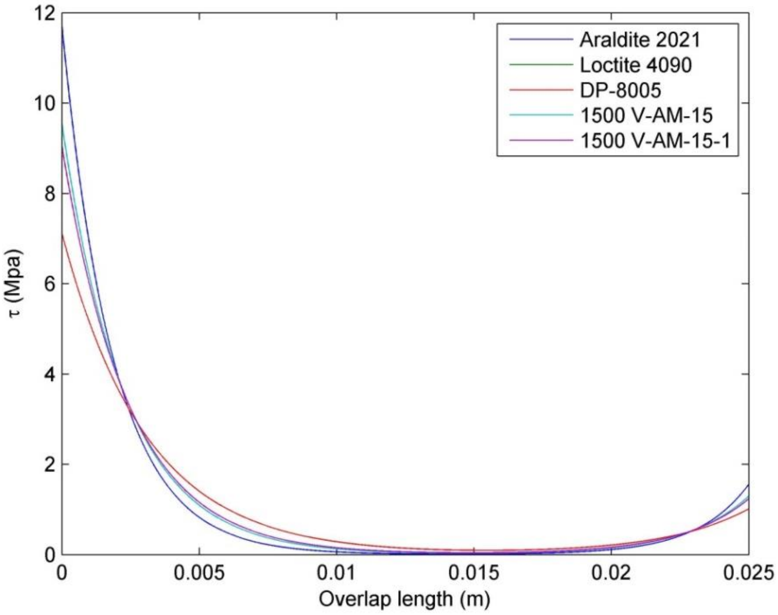


Figure 22: Stress distribution, lap shear, GFR PA-Steel

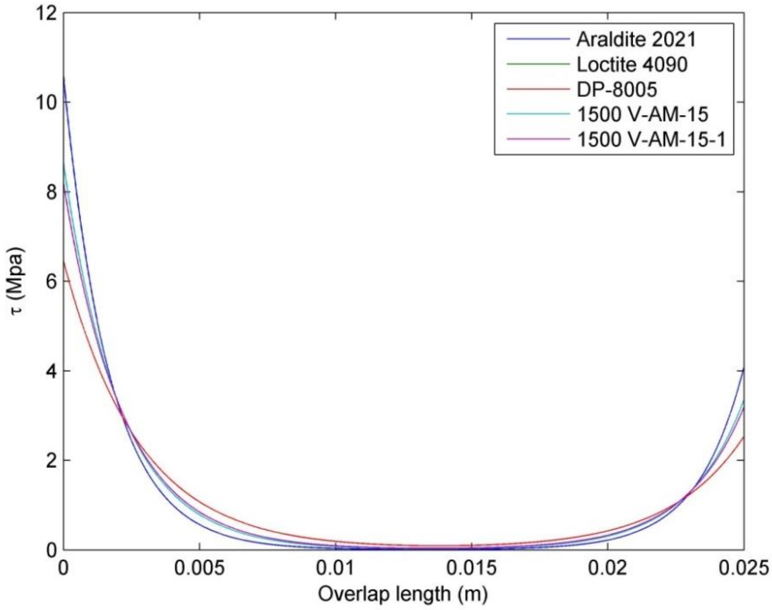


Figure 23: Stress distribution, lap shear, GFR PA-Aluminium

10. Lap shear experiments

All lap shear test were performed on a Zwick 1474 tensile tester. Each specimen was measured prior to the lap shear tests to accurately calculate the shear stress, because every sample will have a slight difference in overlap area. Also the thickness of the adhesive is measured, Table 16 shows the average thickness that was found for each adhesive. The araldite 2021 and DP-8005 adhesives both had the optimal thickness, as specified by the manufacturer. The adhesive layer thickness of the 1500 V-AM-15 and 1500 V-AM-15-1 should be between 0.1 and 0.2 mm, for optimal strength. However, all of the prepared specimens have an adhesive layer which is thinner than the values prescribed by the manufacturer. This was probably caused by a too large pressure on the adhesive, causing the adhesive to flow out to the sides. A too thin adhesive layer could have negative effects on the lap shear strength, but this will become apparent from the tests. The optimal thickness for Loctite 4090 was not specified by the manufacturer so this could not be confirmed if it is the appropriate thickness.

Adhesive	Thickness
Araldite® 2021	0.1
Loctite® 4090	0.04
Scotch-Weld™ DP-8005	0.12
Cyanoacrylate 1500 V-AM-15	0.02
Cyanoacrylate 1500 V-AM-15-1	0.02

Table 16: Average adhesive thickness

10.1 Results

Figure 24 to Figure 29 show the results of the lap shear tests that were performed, all individual results are shown in Appendix A. Almost every adhesive gave quite a large deviation in the lap shear strength. These deviations do not really look related to the difference in thickness of the adhesive layers, as the strengths also deviates on specimen with the same adhesive thickness. However, for the adhesives 1500 V-AM-15 and 1500 V-AM-15-1 the adhesive thickness could be too thin for every specimen because the layer thickness is significantly lower than the advised thickness.

There are a number of factors which could be related to the large deviations that are found. It could be the alignment of the specimens, because each specimen was adhered individually. This means that not every specimen was aligned in the same way. The misalignment could introduce a rotation in the adhesive layer during the lap shear test. Also the fact that the steel substrates were all slightly bend could induce some deviation in the results for the steel to composite connections.

Another factor that could play a role in creating more deviation is the small rotation angle of both of the clamps, during clamping. This rotation was, in some cases, enough to break the connection. So it is possible that the rotation could have weakened some connections more than others, which could also contribute to a larger deviation.

10.1.1 Steel - PP

Figure 24 shows the lap shear strengths that were achieved using the four adhesives. When taking the deviation into account, the adhesives almost all overlap each other, with an exception of 1500 V-AM-15-1 and Loctite 4090.

Most of the adhesives show a quite large deviation in the average shear stress, except for DP-8005 which only has a deviation of 0.3 MPa. One thing that sets DP-8005 out from the others is that it is a quite flexible adhesive and did not completely break across the entire overlap, instead it only broke at the edges of the substrates where, according to the theoretical model, the stress peaks occur. 1500 V-AM-15 achieved the highest shear stress values, but this was only achieved with half of the specimen. All other specimen failed at a lower stress, these individual results are shown in Appendix A.

When comparing the lap shear strength, Table 17, with the values from Table 9, it is clear to see that DP-8005 achieved its maximum strength for the connection to PP and Loctite 4090 reaches a higher strength than the manufacturer states in the data sheet, which is probably a result of the primer that was used.

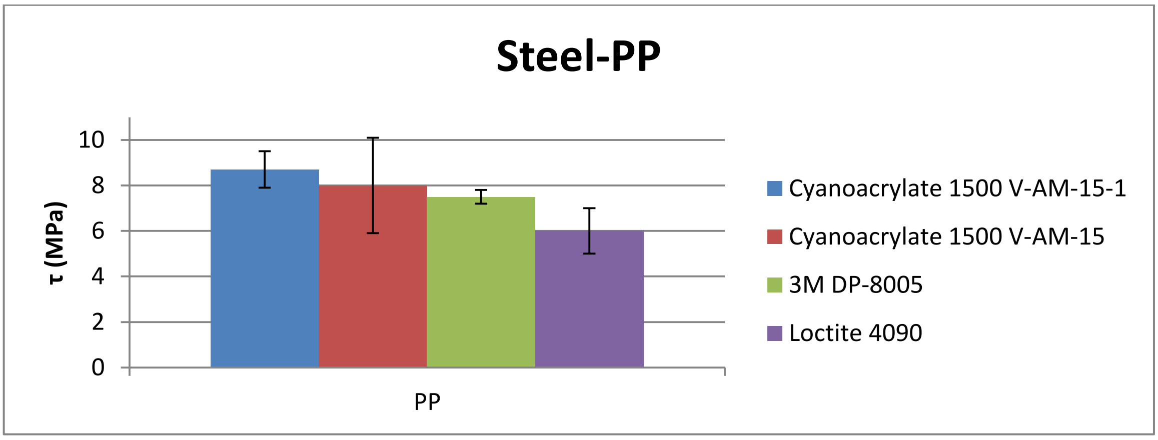


Figure 24: Lap shear test, Steel-PP

Adhesive	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Cyanoacrylate 1500 V-AM-15-1	8.7	0.8	AF (PP)
Cyanoacrylate 1500 V-AM-15	8	2.1	AF (PP)
Scotch-Weld™ DP-8005	7.5	0.3	AF (Alu/PP)
Loctite® 4090	6	1	AF (PP)

Table 17: Results Steel-PP

10.1.2 Aluminium - PP

The lap shear strengths of a connection between aluminium and PP turned out to be lower than the strength that was achieved using steel and PP, the results are shown in Table 18. This was not expected when considering the theoretical model of the lap shear test. There should be lower peak stresses, which should result in a higher average shear stress. However this model only shows the distribution of the stress. This does not mean that the failure is always caused by the peak stress. It could also be the adheres to the aluminium which fails at a lower stress compared to steel. The plastic deformation of the aluminium substrate could also contribute to an unexpected result, because all aluminium substrates adhered with DP-8005 and Loctite 4090 were slightly deformed during the lap shear test. This was also the case for some specimen adhered with the other adhesives, but only the ones with a high lap shear strength. The deformation can induce a small moment on the adhesive layer, which is not included in the theoretical model.

The weak point for the adhesives 1500 V-AM-15-1 and 1500 V-AM-15 was the adherence to aluminium, as all specimen failed on the adherence to aluminium. The shear stresses sometimes exceed 5 MPa, but were mostly around the 3 – 4 MPa. For Loctite 4090 it was the adherence to PP that failed, which also was the failure for the connection of PP to steel. DP-8005 failed on both the PP and aluminium side and managed to achieve the highest strength for the aluminium-PP connection.

Comparison of the maximum shear stresses with the values given by the manufacturers, stated in Table 9, shows again that the DP-8005 is close to its maximum lap shear stress for PP. There is however a little more deviation in the stress, compared to the connection of PP to steel. This is also visible in the results of each individual test, which can be found in Appendix A, where three of the specimen do reach the maximum shear stress. However, the others do not perform as well which causes the average shear stress to drop. Loctite 4090 performs better than the manufacturer indicates, which could again be a result of the primer.

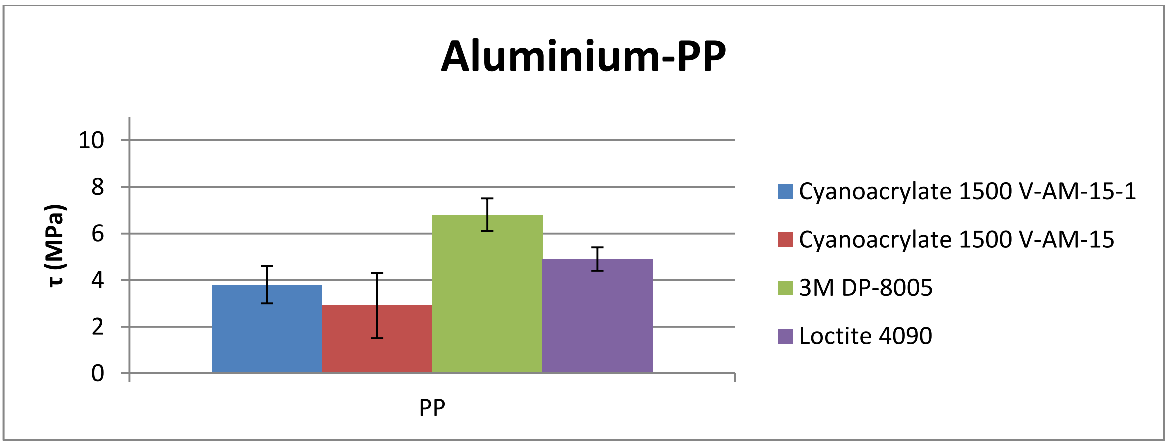


Figure 25: Lap shear test, Aluminium-PP

Adhesive	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Cyanoacrylate 1500 V-AM-15-1	3.8	0.9	AF (Alu)
Cyanoacrylate 1500 V-AM-15	2.9	1.4	AF (Alu)
Scotch-Weld™ DP-8005	6.8	0.7	AF (Alu/PP)
Loctite® 4090	4.9	0.5	AF (PP)

Table 18: Results Aluminium-PP

10.1.3 Steel - PA

The connection of metal to PA is a little bit more complicated compared to the connection to PP, because PA absorbs moisture which could influence its adhering properties. The araldite 2021 adhesive gave quite a low lap shear strength of 4 MPa when combining PA to steel, which was a bit higher than the value that the manufacturer provided, Table 9. However, the connection was also very fragile, the slightest torsion, due to rotation of the clamps, on the specimen could break the adhesive connection. All other adhesives showed a quite high deviation, which could be due to misalignment or damage to the adhesive layer from torsion, induced by the rotation of the clamp. The cyanoacrylates performed quite similar and achieved shear stresses around 6 MPa, just like Loctite 4090 did on the untreated PA. The strength for DP-8005 was lower than 6 MPa for untreated PA, but it managed to get the highest average shear stress when using dried PA.

There is no consistent result to say that the moisture content of PA has any effect on the adhesive properties of PA. DP-8005 was the only adhesive which performed better with dried PA, all others stayed equal or even dropped in strength. The moisture content might have effect on some adhesives, but nothing is really certain with deviations this big. Most adhesives did show some indication that the bonding to PA was better with the dried PA, but this did not always result in a higher shear stress. More research would be required to find out if the moisture content has any influence on the bonding strength of steel to PA.

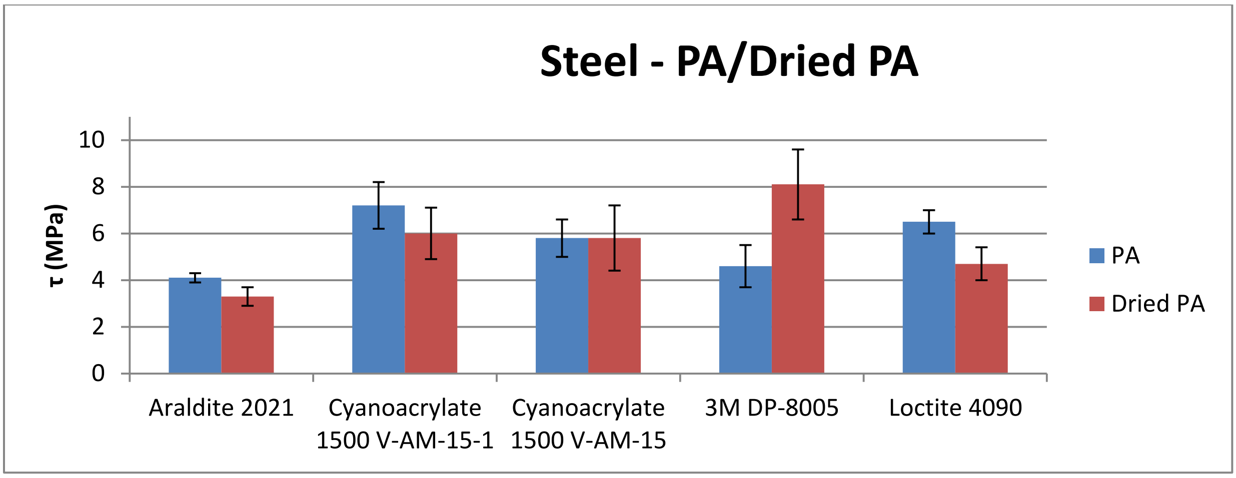


Figure 26: Lap shear test, Steel-PA/Dried PA

Adhesive	Condition	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Araldite® 2021	Untreated	4.1	0.2	AF (PA)
	Dry	3.3	0.4	AF (PA)
Cyanoacrylate 1500 V-AM-15-1	Untreated	7.2	1	AF (PA)
	Dry	6	1.1	AF (PA)*
Cyanoacrylate 1500 V-AM-15	Untreated	5.8	0.8	AF (PA)
	Dry	5.8	1.4	AF (Steel/PA)
Scotch-Weld™ DP-8005	Untreated	4.6	0.9	AF (Steel/PA)
	Dry	8.1	1.5	AF (Steel/PA)
Loctite® 4090	Untreated	6.5	0.5	AF (PA)
	Dry	4.7	0.7	AF (PA)**

*** Slightly more adhesive still on the PA side (compared to untreated)**
**** One specimen had AF on both materials and reach a higher than average stress (6.1 MPa)**

Table 19: Results Steel-PA (Untreated/Dry)

10.1.4 Aluminium - PA

The connection of aluminium to PA gives a lower strength for most of the adhesives compared to steel. Only the DP-8005 adhesive managed to achieve a higher shear stress on aluminium in combination with untreated PA.

The moisture content does seem to influence the lap shear strength, between PA and aluminium, more than it did the connection to steel. Most of the adhesives showed that a lower moisture content seem to have a positive effect on the bonding to PA and the laps shear strength. Cyanoacrylate 1500 V-AM-15-1 showed some improvement, which was also consistent with the failure mode it presented. The connection to the untreated PA failed on one of the two surfaces, either the PA or aluminium side, Figure 27. The highest stresses were reached when the failure occurred at the aluminium side. This happened more often with the dried PA, Figure 28, so this indicates that the adhesive adheres better to the dried PA and also results in a slightly higher shear stress.

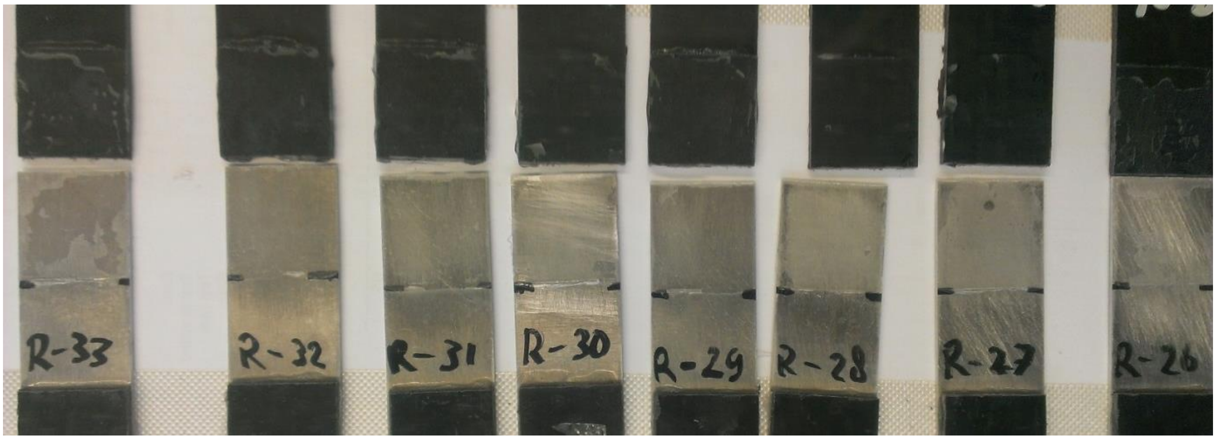


Figure 27: Lap shear results 1500 V-AM-15-1, Aluminium-PA

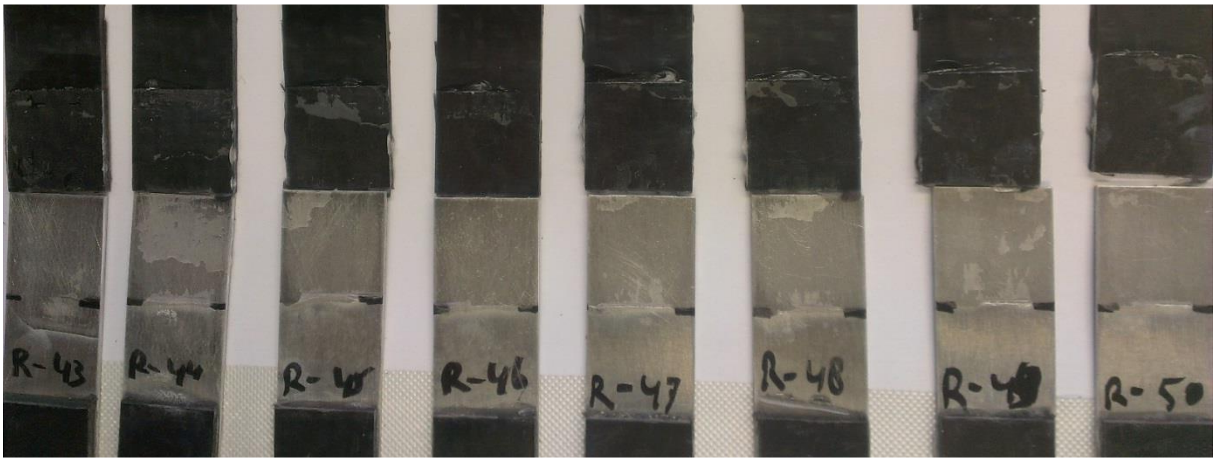


Figure 28: Lap shear result 1500 V-AM-15-1, Aluminium-Dried PA

Loctite 4090 also showed an improvement in shear stress, when comparing dried to untreated PA. The failure mode looks quite similar in this situation, only slightly more adhesive is still attached to the PA side of the dried sample. Also DP-8005 shows a slight improvement where the deviation is reduced and the average stress is increased. The failure mode was more or less the same for this adhesive. The other two adhesives did not benefit from the low moisture content and showed little increase or decrease, which still is within the deviation of the untreated samples.

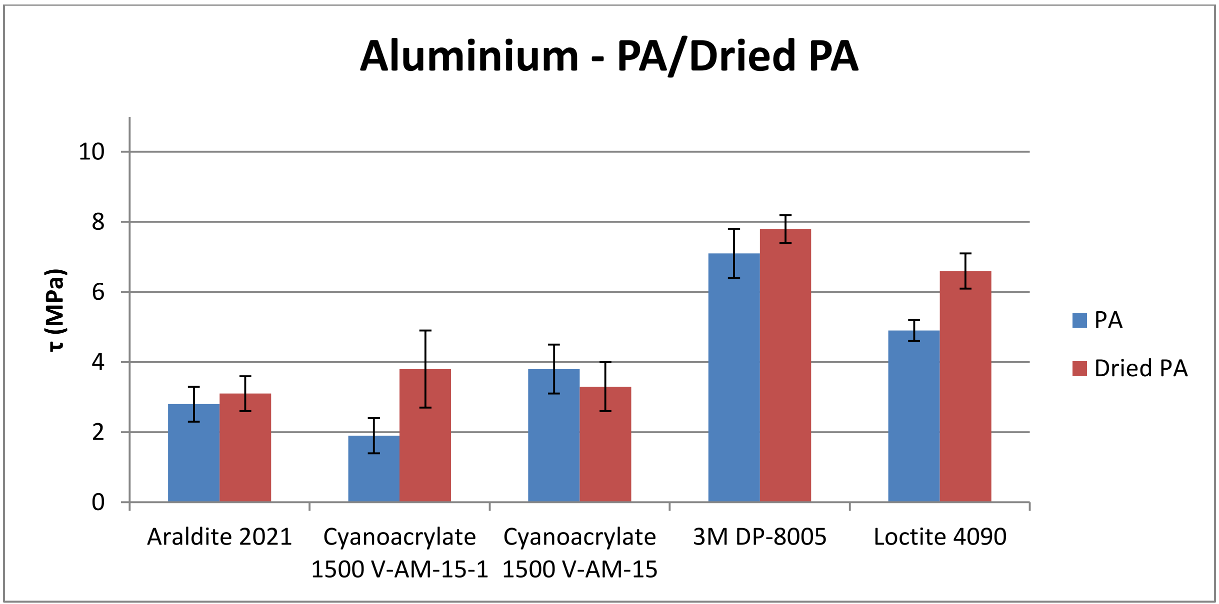


Figure 29: Lap shear test, Aluminium-PA/Dried PA

Adhesive	Condition	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Araldite® 2021	Untreated	2.8	0.5	AF (PA)
	Dry	3.1	0.5	AF (PA)
Cyanoacrylate 1500 V-AM-15-1	Untreated	1.9	0.5	AF (PA) / AF (Alu)*
	Dry	3.8	1.1	AF (Alu)
Cyanoacrylate 1500 V-AM-15	Untreated	3.8	0.7	AF (Alu)
	Dry	3.3	0.7	AF (Alu)
Scotch-Weld™ DP-8005	Untreated	7.1	0.7	AF (Steel/PA)
	Dry	7.8	0.4	AF (Steel/PA)
Loctite® 4090	Untreated	4.9	0.3	AF (PA)
	Dry	6.6	0.5	AF(Alu/PA)

*** Specimens either failed on aluminium or PA side**

Table 20: Results Aluminium-PA (Untreated/Dry)

10.2 Evaluation of the adhesives

The adhesives can be evaluated now that all lap shear tests have been performed. There is some variation in the strengths that are achieved with each adhesive on the different materials. Almost all adhesives show a large difference in the adherence to steel compared aluminium, where the highest strengths are mostly achieved on a steel-composite connection.

10.2.1 Araldite 2021

Araldite 2021 is not suitable for adhering PP to steel or aluminium because there is absolutely no bonding to the surface of PP. It's adhering property to PA is also not very good, which is the reason why some of the samples failed when the clamps, of the tensile tester, were tightened and the specimen was slightly rotated.

The maximum stress that the adhesive can achieve is quite low, 4 MPa when adhering steel to PA and almost 3 MPa when adhering aluminium to PA. These values match the lap shear strength provided in the data sheets of the adhesive [28], so there is not much room for improvement on this strength. The moisture content had little effect on the adhesion properties to PA, but it did show a small decrease in maximum stress when dried PA was adhered to steel compared to the untreated PA.

Araldite 2021 does not show any potential of combining the chosen metals to composites. The strength of the adhesive to metals is very good, but it fails on the adherence to the composites. It is possible that surface treatments could increase the adhesion properties to PP or PA and increase the maximum shear stress. However, based on the results from the lap shear test it can be concluded that Araldite 2021 is not applicable as a structural adhesive for connecting composites with metals.

10.2.2 Cyanoacrylate 1500 V-AM-15-1

Cyanoacrylate 1500 V-AM-15-1 shows a good potential in combining steel and glass fibre reinforced PP, as it achieved the highest average stress for this combination of materials. There was however a large deviation in the stress that was achieved. This could be caused by the thickness of the adhesive, which was thinner than the 0.1 to 0.2 mm that the manufacturer prescribed. The strength of the adhesive dropped significantly when the steel substrate was replaced with an aluminium substrate. In this case, the failure mode was the connection of the adhesive to the aluminium.

The lap shear strength of steel and PA was lower compared to steel and PP, but the adhesive still managed to get a relatively high strength on untreated PA, compared to the other adhesives.
Drying the PA showed a decrease in strength, but with a rather large deviation which overlaps the strength of untreated PA. The failure mode showed that the adhesive had a better connection with the dried PA as more adhesive stuck to that side after failure, but somehow this also had effect on the adhesion to steel. The adhesion to aluminium and PA showed a lower strength compared to steel and PA. Drying of the PA resulted in an increase in strength and the failure modes showed again that there was a better adherence to PA.

Drying of the PA shows a better adherence to PA, as the failure modes show more adhesive still on the PA side, compared to the untreated PA. But this does not always mean that the strength increases. This was only the case for the connection to aluminium.

1500 V-AM-15-1 shows potential in connecting PP and PA, but only in combination with steel. The strengths that were achieved using aluminium are too low for a structural bond. The only downside is that there is a rather large deviation in strength, which could be due to the thin layer of adhesive or caused by other factors. If this deviation could be reduced, the adhesive would be a good choice in adhesive bonding between steel and composite.

10.2.3 Cyanoacrylate 1500 V-AM-15

1500 V-AM-15 is capable of achieving lap shear strengths up to 9 MPa, when adhering steel to PP, but only half of the specimens reached this strength. The other specimens reached to about 6 MPa, which is quite a large difference. The strengths were much lower on the connection between aluminium and PP. The failure here was the adhesion to the aluminium, which also was the problem with 1500 V-AM-15-1. The strength in connections with PA were lower, compared to PP, but also with a large deviation. The difference in moisture content showed no significant difference in strength for both the connection to steel and aluminium.

The 1500 V-AM-15 looks like a good adhesive for adhering PP to steel, but not for adhering PP to aluminium. The maximum stresses that were achieved on PP and aluminium are too low for a structural connection. Addition testing is required to see if this adhesive can produce a stable and strong bond as the current results show a large deviation for the connection to PP. If this deviation could be reduced, by for example better controlling the alignment of the substrates or adhesive thickness, the strength might go up. This could also make the adhesive more suitable for a connection of PA to steel. The connection to aluminium however will most likely still be too weak for a structural connection.

10.2.4 3M DP-8005

DP-8005 was the most flexible adhesive, out of the five adhesives that were tested. Most of the samples broke on one edge of the adhesive layer, which was gave a large enough drop in force for the tensile tester to think the specimen broke. However the substrates were still attached to each other.

The adhesive achieved a stable connection between steel and PP with little deviation. The connection to aluminium was a little bit weaker and also had more deviation, but it was the strongest bond that was achieved for the combination of aluminium and PP. Both lap shear strengths that were found during the lap shear tests are very similar to the maximum shear stress that is prescribed by the manufacturer. The effect of drying the PA showed a consistent result for this adhesive. The strength of the connection to steel increases drastically and the connection to aluminium was slightly stronger and had a lower deviation. There is however not much difference in the failure modes of the adhesive that could explain why the strength increases.

3M's DP-8005 seems to be a stable adhesive to adhere PP to steel, the adhesive also reached the highest strength in the connection of PP to aluminium but there was a little more deviation in the strength compared to PP on steel. This is the opposite of what happened to the connection of PA to steel and aluminium, where aluminium gave a higher strength for the untreated PA samples. The dried samples managed to get a strength which was equal for both steel and aluminium, only the connection to steel had a larger deviation.

10.2.5 Loctite 4090

The Loctite 4090 adhesive has a similar performance on PP and PA. The achieved maximal stresses for PP and the untreated PA are equal to each other for steel and for aluminium. However, the strengths with the connections to aluminium are lower than the strengths that are achieved with steel. Drying the PA had a negative influence on the connection to steel and a positive influence for the connection to aluminium. So the moisture content of the PA will have a different effect on the adhesive depending on the material it is adhered to. The shear stress that was achieved on PP exceeded the maximum that was given by the manufacturer for both steel and aluminium connections. This increase was probably caused by the primer that was used.

The Loctite 4090 adhesive was not able to achieve high strength bonds with either PP or PA, but the deviation in maximum stress is quite low, compared to the other adhesives. This low deviation gives the indication that there is not much more to gain in strength by for example better aligning the substrates or increasing the thickness of the adhesive. It maybe that additional surface treatments or increasing the adhesive thickness could enhance the strength. Based on the lap shear test results, this adhesive does not look like a good adhesive for structural connections.

11. Additional experiments

Additional experiments were performed to see if the connections could be improved and if the testing method gives a good indication on what the adhesives are capable of. The first experiment will be to see if increasing the thickness of the composite part would result in a higher average shear stress. The increase in thickness should result in a lower peak stress at the edges according to the theoretical model, which should mean that the average stress can increase. The second test that is performed is the double lap shear test, to see if the single lap shear method was indeed the best method for testing the adhesive strength or if the double lap shear would provide a better overview of what the adhesive can achieve. The final experiment is to see if the 1500 V-AM-15 adhesive can perform better if the adhesive thickness is within the values that were specified by the manufacturer. The speed for all additional tests was kept equal to the testing speed of the single lap shear test.

11.1 Lap shear test with a thicker composite part

According to the theoretical model, explained in chapter 9, the peak stresses on the edges of the adhesive layer can be shifted towards a more equal distribution by adjusting the thickness of the composite part. This could be interesting, because this could result in an increased lap shear strength. Another lap shear experiment was performed with a thicker composite part, to test if this would really improve the lap shear strength. The composite material for this test is a 4 mm glass fibre reinforced polyamide, which has not been dried. Loctite 4090 was chosen as the adhesive, because this was one of the adhesives which had the most constant lap shear strength when used on PA in combination with steel and aluminium.

Figure 30 and Figure 31 show how the stress distribution will be when the PA is increased in thickness compared to the original situation. According to the model, the peak stress will drop with 6 MPa for steel and aluminium. The peak stress for the normal lap shear, with a $\tau_m$of 6.5 MPa, was 117 MPa. With the reduction of the peak, the τ_m that should be reached according to the model lies somewhere around the 9.75 MPa for a connection to steel. For aluminium, the τ_m should increase from 4.9 MPa to almost 7.8 MPa.

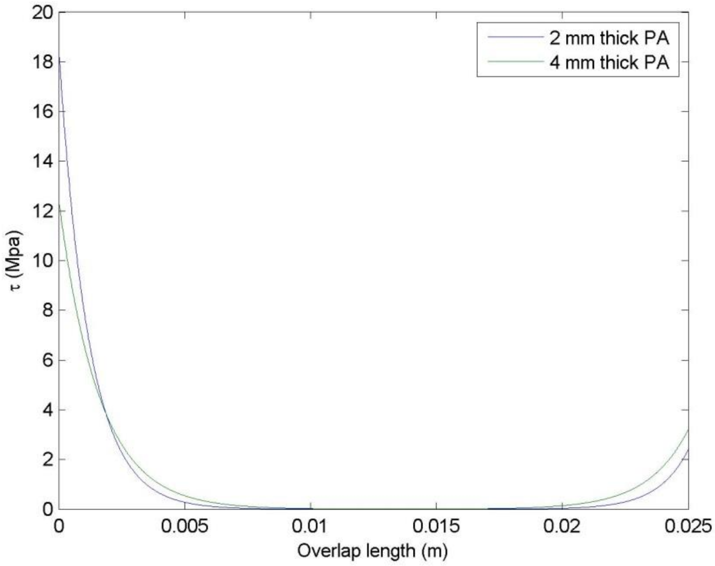


Figure 30: Theoretical model, Steel-PA

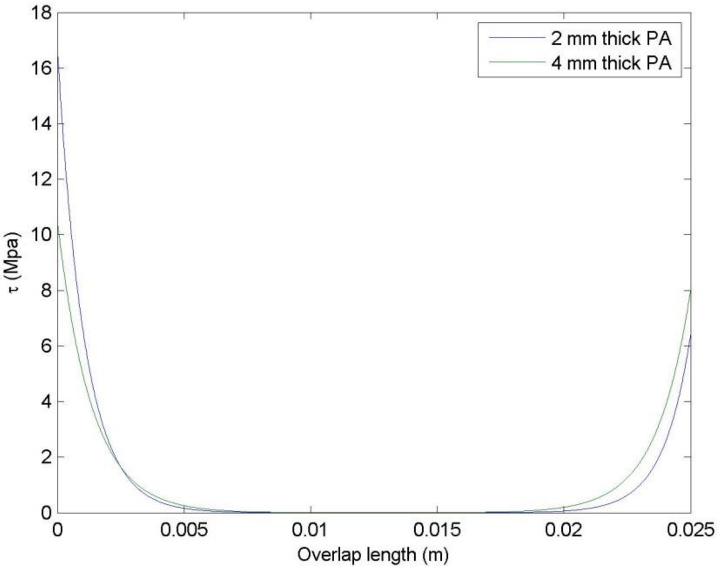


Figure 31: Theoretical model, Aluminium-PA

Figure 32 shows how the setup will be for the lap shear test with an increased thickness of the composite part.

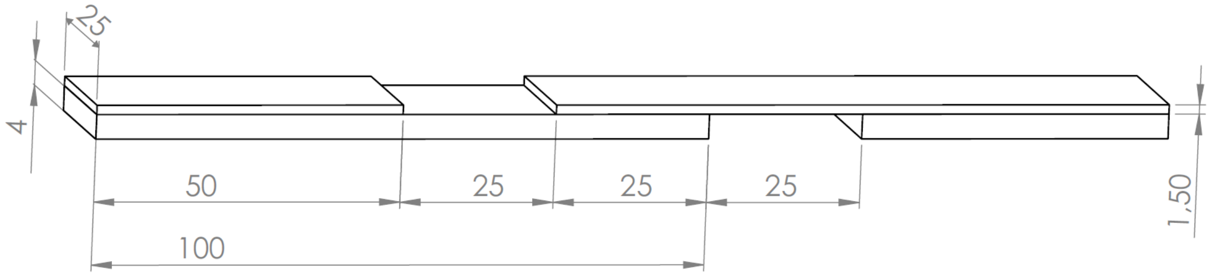


Figure 32: Setup for the thicker lap shear test

11.1.1 Results

The results of the thick lap shear test are shown in Figure 33 and show an unexpected result. The expectation of an increased lap shear strength is not shown in the results of the test, which shows an almost equal result to the single lap shear test that was performed. These results indicate that the failure of the adhesive layer might not be related to the stress peaks. The model does not take the different adherence properties to both materials into account. This property is not equal for the materials that are joined together. This could be the reason why the model cannot be used to predict the shear stress at which the connection will fail. The failure modes do however show some small differences between the first test and the test with the ticker composite part. The failure, in the case for the 4 mm composite part, showed adhesive failure on both substrates instead of only on the PA side, which was the case with the 2 mm composite part. So there is a difference between both tests, but this does not show in the results of the lap shear strength, which are stated in Table 21.

Adhesive	Condition	Metal	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Loctite® 4090	Untreated	Steel	6.5	0.5	AF (PA/Steel)
Loctite® 4090	Untreated (4mm)	Steel	6.2	1.2	AF (PA/Steel)
Loctite® 4090	Untreated	Aluminium	4.9	0.3	AF (PA/Alu)
Loctite® 4090	Untreated (4mm)	Aluminium	4.1	0.4	AF (PA/Alu)

Table 21: Lap shear strength with different thickness of PA

The conclusion of this test is that changing the thickness of the composite part does not contribute to a higher lap shear strength.

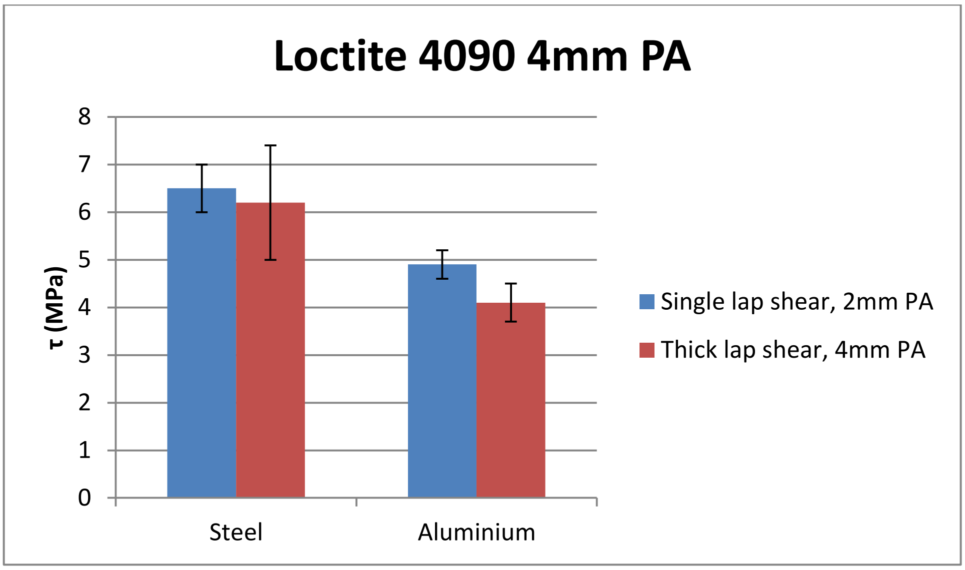


Figure 33: Thick lap shear test

11.2 Double lap shear test

The double lap shear test will be performed using two substrates of glass reinforced PP as the composite parts. These parts will be adhered to steel and aluminium parts using the DP-8005 adhesives, which is chosen because it showed the lowest deviation in shear stress when used on PP and the highest strength for the combination of aluminium and PP. The preparation of the double lap shear specimens was not as easy as preparing the single lap shear specimen because of the two adhesive layers and the short working time of the adhesive. The setup is shown in Figure 34, where two substrates of 2 mm PP are used on the left and the metal on the right. One glass tab, 1.5 mm thick, is used to keep the distance between the two PP substrates.

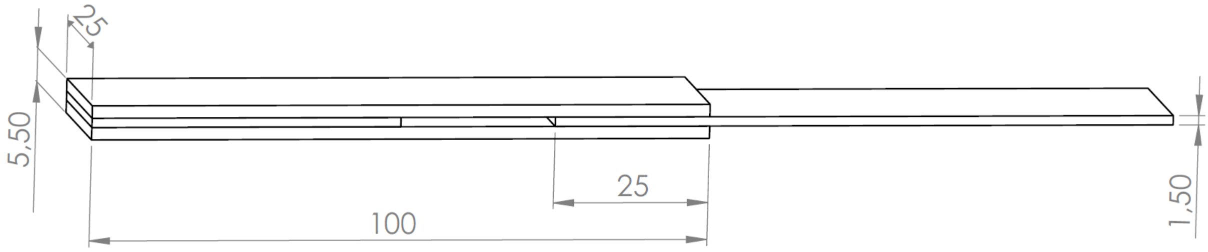


Figure 34: Setup for double lap shear test

11.2.1 Results

The results of the double lap shear are compared to the single lap shear and shown in Table 22 and Figure 37. This clearly shows a larger shear strength for the connection of PP to steel for the double lap shear method, but this was only the case when both sides of the double lap failed at the same time. Two specimen failed on one adhesive layer and showed a strength which was equal to the single lap shear strength, result of individual test can be found in appendix A. Figure 35 shows the failure mode of one specimen which broke on both sides at the same time. This shows that structural failure has occurred at two places on the PP side.

Figure 35: Failure of the double lap shear, Steel-PP

The aluminium double lap shear did not give the same results as the steel double lap shear did. Both sides started slipping on the adhesive which reduced the force on the specimen, this slipping is shown in Figure 36. The double lap shear test using aluminium resulted in a similar result for the average stress as the single lap shear test.

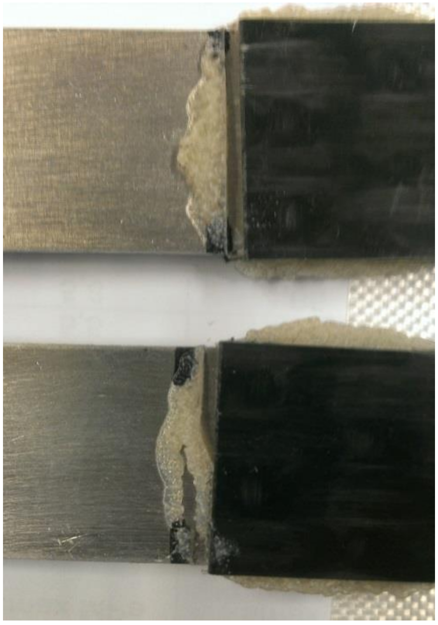


Figure 36: Failure of the double lap shear, Aluminium-PP

The double lap shear test can result in higher lap shear strengths compared to the single lap shear test. This is probably because of the alignment, which will be better with the double lap shear as the materials tend to bend during a single lap shear, introducing a peeling force. The slippage, which occurred during the aluminium double lap shear test, could be an effect of the adhering properties to the aluminium because the strength to aluminium is a bit lower than the strength to steel, or it could be because of the flexibility of the adhesive itself.

Adhesive	Lap shear type	Metal	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Scotch-Weld™ DP-8005	SLS	Steel	7.5	0.3	AF (PP/Steel)
Scotch-Weld™ DP-8005	DLS	Steel	10.2	0.5	AF (PP/Steel) / SF (PP)
Scotch-Weld™ DP-8005	SLS	Aluminium	6.8	0.7	AF (PP/Alu)
Scotch-Weld™ DP-8005	DLS	Aluminium	6.1	0.5	AF (PP/Alu)

Table 22: Lap shear strengths, single and double lap shear

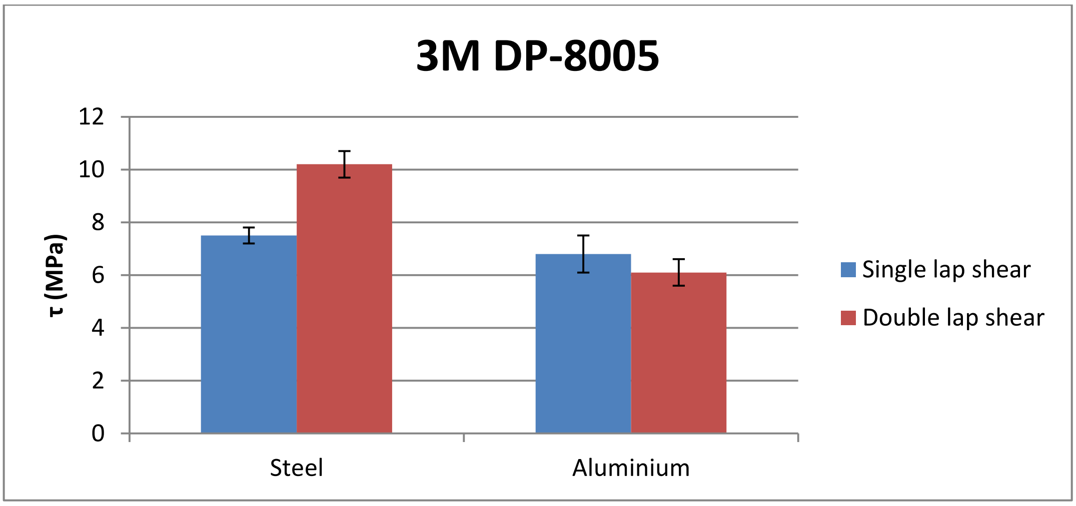


Figure 37: Results double lap shear test

The double lap shear test can produce higher strength bonding, but this will only be the case if both sides fail at the same time. Otherwise it will just give the result of the single lap shear test. This indicates that the single lap shear test is a good method to get an idea of what each adhesive is capable of. The double lap shear test is a bit more complicated and will only produce good results if both sides fail at the same time.

11.3 Lap shear 1500 V-AM-15

The 1500 V-AM-15 managed to achieve a high lap shear strength when adhering steel to PP, but the strength had a large deviation. A additional test was performed to find out if this deviation was caused by a too thin adhesive layer. Glass beads, 106 to 212 µm thick, were added to the adhesive to keep the distance between the two parts. This is not easy to accomplish, as the adhesive cures very fast. The amount of glass beads was determined based on the area of the surface that is adhered. A total of 0.23 grams would be enough to cover the entire area of 25 by 25 mm. To minimize the effect of the glass beads, only enough glass beads to cover a quarter of the surface will be added. However, not all of the glass beads could be applied to the surface because the adhesive starts curing during mixture. Each specimen will therefore have a different amount of glass beads in the adhesive layer.

One downside of increasing the thickness of the adhesive is that it also increases the curing time of the adhesive. It will take more time before the adhesive reaches its minimal strength. This can however be accelerated by using an activator. When this is sprayed directly on the adhesive, it will start curing immediately. This will only affect the edges of the adhesive, but it will make it possible to move the two parts that are connected, while the rest of the adhesive is still curing because the edges are already cured. The activator is not used in these experiments, because it is unknown if this will also affects the strength of the adhesive.

11.3.1 Results on PP

Adding the glass beads increased the average thickness of the adhesive from 0.02 mm to 0.15 mm, which is exactly within the desired range of thickness. Results of the lap shear test are shown in Figure 39 and look very promising. The average stress is increased by almost 40% and the deviation reduced by more than 50%, the data is shown in Table 23.

Adhesive	Adhesive thickness	Metal	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Cyanoacrylate 1500 V-AM-15	0.02	Steel	8	2.1	AF (PP/Steel)
Cyanoacrylate 1500 V-AM-15	0.15	Steel	11.2	1	AF (PP/Steel) / SF (PP)

Table 23: Lap shear strength 1500 V-AM-15, Steel-PP

The failure mode shows some small residue of the PP substrate still on the steel substrates, which is hard to see but shown in Figure 38. This indicates that the failure mode was a combination of adhesive failure and structural failure, which means there was a better connection with the PP than in the previous lap shear test. This shows that the thickness of the adhesive is a very important factor for this adhesive. The presents of the glass beads, which are a pollution in the adhesive layer, do not show any negative effect. It would be ideally if the glass beads were already pre-mixed within the adhesive. This way the mixing by hand would not be necessary anymore and the thickness would always be within the right range.

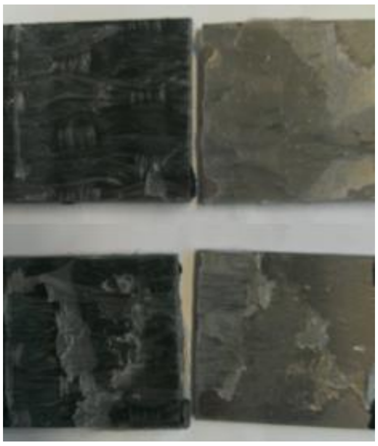


Figure 38: Failure mode 1500 V-AM-15, Steel-PP

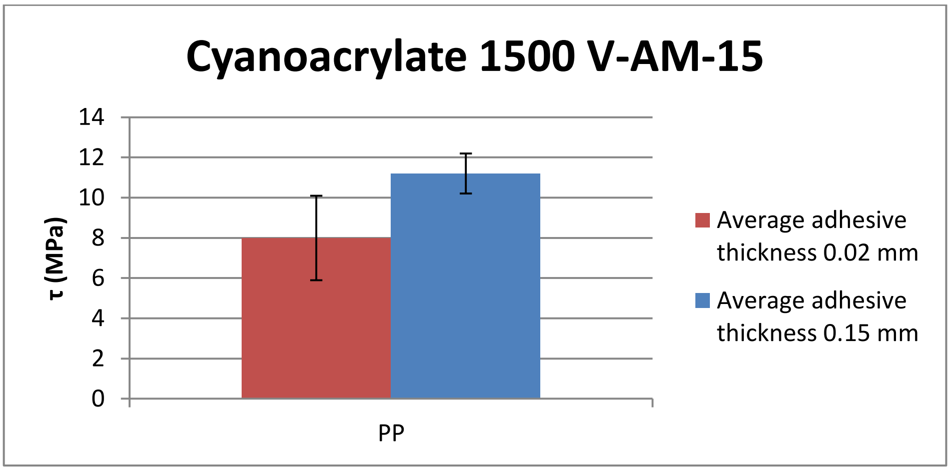


Figure 39: Results adhesive thickness controlled 1500 V-AM-15, Steel-PP

11.3.2 Results on PA

The adding of glass beads to the adhesive showed the same results for steel-PA as it did for steel-PP. Only this time the increase in lap shear strength was even larger. The shear stress was twice as high as a result of the increased adhesive thickness, but also the deviation increased more than twice as much. Table 24 shows a comparison of the shear stresses between the two adhesive thicknesses. The lowest stress found during the lap shear test was 9.8 MPa and the highest 16.8 MPa. This large deviation could be a result of the mixing of the glass beads with the adhesive, because not every adhesive layer has the same amount and distribution of beads.

One specimen was left out of the results because the adhesive layer was twice as thick as the rest of the specimen. This difference in thickness is quite significant and the result of the lap shear was a little lower than the other specimen and is therefore not included in the results. It managed to get a lap shear strength of 9.1 MPa, with an adhesive thickness of 0.27 mm.

Adhesive	Condition	Adhesive thickness	Metal	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Cyanoacrylate 1500 V-AM-15	Untreated	0.02	Steel	5.8	0.8	AF (PA)
Cyanoacrylate 1500 V-AM-15	Untreated	0.15	Steel	12.6	2.4	AF (PA/Steel)

Table 24: Lap shear strength 1500 V-AM-15, Steel-PA

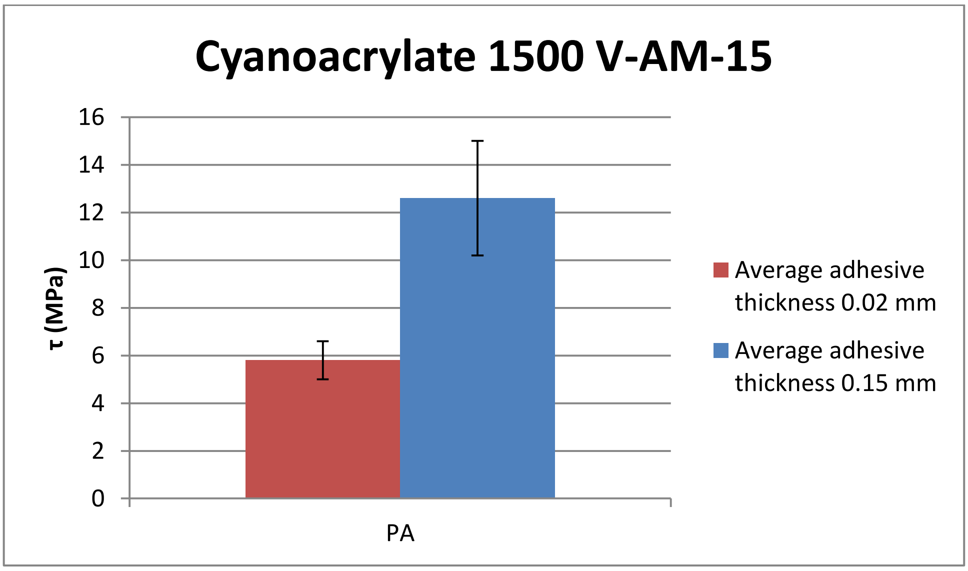


Figure 40: Results adhesive thickness controlled 1500 V-AM-15, Steel-PA

The increase in thickness shows a large improvement for this adhesive. There is however still a large deviation, which could be a result of the mixing or misalignment of the substrates. However, it could also be the bonding to the PA that results in the large deviation. Each specimen mostly had adhesive failure on the PA side. Except for one, where the failure occurred purely on the steel side. This specimen managed to get a strength which was a little above average.

12. Adhesive modification

The results of the cyanoacrylates were shared with the manufacturer of the cyanoacrylates, Ruplo Lijmtechniek, who also performed their own adhesion tests on the same PP and PA samples. They wanted to see how well the bonding was, with their adhesives, and if there was some improvement possible by adjusting the formula. Three new bottles with different formulas were created which should have better bonding properties with both PA and aluminium. These adhesives are: 1500 V-MOW-3, 1500 V-551-5 and 1500 V-DI-PROP. Unfortunately there were not enough steel and aluminium substrates left to test all of these adhesives. So only 1500 V-MOW-3 was tested to see if this formula gave a better result for the connections of steel and aluminium to PA, this was done in combination with the provided primer, PE/PP-5.

12.1 Cyanoacrylate 1500 V-MOW-3

Two lap shear experiments were prepared for this adhesive, one with steel and PA and the other with aluminium and PA. The adhesive will be mixed with the same amount of glass beads as used in the previous lap shear test with the 1500 V-AM-15 adhesive.

The average thickness of the adhesive layer turned out to be a little bit thicker than the thickness of the previous tests. There were however two specimen with adhesive layers that were even thicker. The average thickness was 0.18 mm with two outliers that have a thickness of 0.22 and 0.25 mm. The average adhesive thickness for the aluminium to PA connection, 0.26 mm, was a bit higher than all the previous layers. It is unknown why these layers were all thicker than the others, but it might be related to the hand mixing and quick curing of the adhesive.

Table 25 and Figure 41 show the results of the lap shear test with 1500 V-MOW-3 compared to 1500 V-AM-15. This shows that there is no improvement with this variant of cyanoacrylate. The failure mode for 1500 V-MOW-3 was mostly on the PA side for the connection to steel. There was a lot of deviation in the results, where the maximum was 16.5 MPa and the minimum only reached 6.7 MPa. The failure mode for the aluminium-PA connection was the bonding to aluminium that failed.

Adhesive	Condition	Adhesive thickness	Metal	Avg. stress (MPa)	Deviation (MPa)	Failure mode
Cyanoacrylate 1500 V-AM-15	Untreated	0.15	Steel	12.6	2.4	AF (PA/Steel)
Cyanoacrylate 1500 V-MOW-3	Untreated	0.18	Steel	11.6	4.0	AF (PA)
Cyanoacrylate 1500 V-AM-15	Untreated	0.02	Steel	3.8	0.7	AF (Alu)
Cyanoacrylate 1500 V-MOW-3	Untreated	0.26	Alu	4.3	0.5	AF (Alu)

Table 25: Comparison between 1500 V-AM-15 and 1500 V-MOW-3 for PA-metal connections

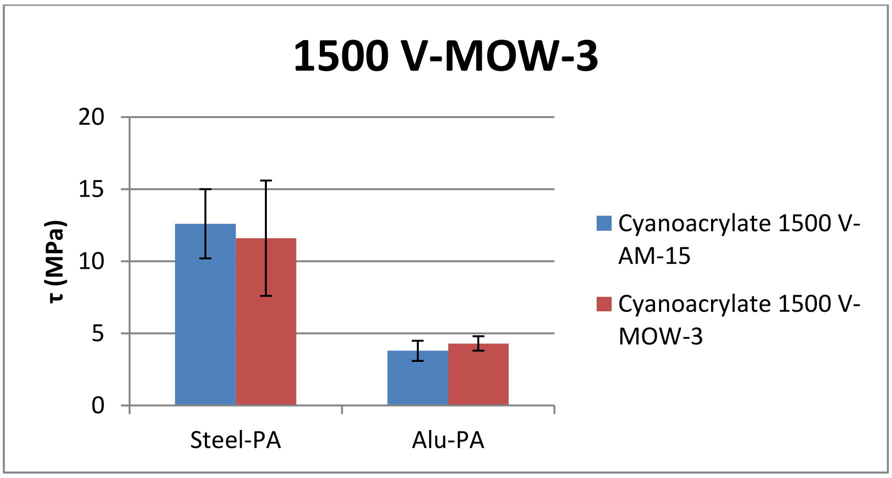


Figure 41: Comparison, 1500 V-AM-15 and 1500 V-MOW-3

The tested variant of cyanoacrylate did not show any improvement for the connection to PA. The thicker than average adhesive layers did however show the highest strengths, with the connection to steel. Also the highest strengths, for the connection with steel, showed more adhesive still on the PA side after failure. All aluminium connections failed purely on the adhesive bonding to aluminium.

It could be that the two other adhesives show a different result, but this could unfortunately not be tested.

13. Conclusion

The joining of composites and metals using adhesives is not as easy as it sounds. Both materials have completely different bonding properties which makes it hard to find an adhesive that adheres well to both materials. Most adhesives can achieve good bonding strengths with metals but the adhesion to PP and PA is usually much lower. Five different adhesives were chosen based on their ability to bond with metals, PP and PA. Also their curing time and resistance to environmental effects played an important part in deciding which adhesive was suitable for the connection between metals and composites.

A testing method was required to compare the adhesives with each other. The intention was to create a structural connection between metal and composite. The single lap shear test was chosen, because it is a simple testing method and gives a good indication of what each adhesive is capable of. A good structural adhesive connection should be able to handle at least 6.9 MPa of shear stress, during a single lap shear test, to be qualified as a structural adhesive. The goal is to find a structural adhesive for each combination of materials.

The results of the lap shear tests show that not every adhesive adheres as well to each type of material. Especially the cyanoacrylate adhesives showed a large difference in lap shear strength between steel and aluminium connections. Araldite 2021 was the only adhesive which did not adhere to PP, even with the use of primers. It managed to reach a strength of 3 to 4 MPa for the combination of PA with steel and aluminium. This was exactly the stress that the data sheet for this adhesive prescribed. Making it unsuitable for a structural connection. Loctite 4090 was also unable to create a structural connection with any combination of materials. It did however reach a higher lap shear strength for the connection of PP to metal than was indicated in the data sheet, but this was not enough to create a structural bond. Cyanoacrylate 1500 V-AM-15 and 1500 V-AM-15-1 did manage to create a structural connection between PP and steel. 1500 V-AM-15-1 also managed to get this result for steel and untreated PA, but all other connections did not manage reach this strength. DP-8005 was the adhesive which reached a shear stress around 7 MPa for almost each connection. The only exception was for the combination of untreated PA and steel.

Almost every adhesive showed quite a large deviation in the average shear stress, which could be caused by a number of factors. The factors that could have caused these deviations are:

- Too thin adhesive layer thickness
- Misalignment of the two substrates
- Unequal adhesive outflow at the edges
- Rotation of the clamp during clamping
- Slightly bended steel substrates
- Insufficient surface treatment

The adhesive layer thicknesses for the cyanoacrylate adhesives both were too thin. Both adhesives had an average thickness of 0.02 mm instead of the specified 0.1 to 0.2 mm thickness. This difference is large enough that it could influence the strength of the adhesive. The alignment of each specimen is different, as it is nearly impossible to place each substrate perfectly onto the other. The amount of adhesive that flows out of the connection also has a small contribution to the lap shear strength [35]. This amount will however not be the same for each specimen, which could contribute to a small deviation.

The tensile tester also could have had a contribution to the deviations, because the clamps slightly rotate during clamping. This rotates the specimen which was, for some specimen, enough to break the adhesive layer. Chances are that it could also have weakened some of the adhesive layers. The steel substrates them self could also have caused some deviation in the steel-composite connections. All steel substrates were slightly bend, which could have induce some peeling during clamping, because the substrates could not be properly aligned. Another possibility is that the surface treatments were not sufficient enough for every substrate. Dust particles in the adhesive layer, or insufficient sanding of the substrates could have influenced the bonding of the adhesives.

Additional experiments were performed before concluding which adhesive is the best choice for each combination of materials. The first experiment was performed to verify a theoretical model, Klein/Li, to see if it could be used to improve the lap shear strength. The model showed that the stress distribution would have lower stress peaks, at the edges of the overlap, by increasing the thickness of the composite part, or reducing the thickness of the metal. Results showed that there was no increase in the average shear stress, which means that the model cannot always be applied to the combination of metal and composite. The second experiment was a double lap shear test. This showed that the double lap shear could result in higher shear stresses for some connection. For others, it will give a shear stress which is almost equal to the single lap shear test. This shows that the single lap shear test is a sufficient enough test to get an indication of what each adhesive is capable of. The double lap shear can improve the strength, which is most likely a result from the alignment that reduces the bending of the substrates and creates a purely shear load on the adhesive.

Another test was performed on the cyanoacrylate 1500 V-AM-15, because the adhesive thickness was not within the range that was specified by the manufacturer. This test should show if the strength of the adhesive increases when the adhesive is at its proper thickness. Glass beads were added to the adhesive layer, which kept the distance between the two substrates so that to desired adhesive thickness could be reached. Increasing the adhesive layer thickness showed an increase in lap shear strength and there was also a smaller deviation for the connection of steel to PP. Steel to PA also increased in strength but the deviation also increased.

The manufacturer of the cyanoacrylate adhesives, Ruplo Lijmtechniek, developed new adhesives which should give a better bond to PA and to aluminium. One of these adhesives was tested on the connection of PA to steel and aluminium. Unfortunately it did not give the expected result, but gave a more or less equal result as was achieved with the 1500 V-AM-15 adhesive.

Table 26 shows the best adhesive for each combination of materials based on the results from the lap shear tests. This shows that the 1500 V-AM-15 adhesive is the best adhesive to use on steel-composite connections. Based on the requirements of a certain application, 1500 V-AM-15-1 could also be used as it should have better impact and shock resistance. DP-8005 is the best choice when bonding aluminium to composites. The strength will not be as high as the 1500 V-AM-15 reaches on steel, but it still is a structural connection for the bonding to PA. The bonding to PP almost has a structural bond, half of the specimen did reach a strength that was good enough for a structural bond. Better alignment of the specimen or additional surface treatments should make it possible to increase the bond enough for this connection to be a structural bond.

Combination	Best adhesives	Avg. Shear stress (MPa)
Steel - PP	Cyanoacrylate 1500 V-AM-15	11.2
Aluminium - PP	3M DP-8005	6.8
Steel - PA	Cyanoacrylate 1500 V-AM-15	12.6
Aluminium - PA	3M DP-8005	7.8

Table 26: Best adhesive for each combination of materials

The result of this report is that it is possible to establish a hybrid connection between metal and composite with the use of adhesives. It is even possible to get a so called structural connection, which are the connection that reach a lap shear strength of at least 6.9 MPa, between the two materials. Except for the connection of aluminium to PP, which will require some additional testing with different surface treatments to increase the strength. There are however stronger, slow curing, adhesives available on the market and there are also other methods to could be used to connect metals to composites like welding and mechanical connection. To find out how good the adhesive connections, that were created during this research, are, they would have to be compared to results of these other connection methods.

There was no data found for metal-composite connections using mechanical connection. There is however data about ultrasonic welding and adhering of metal to composite using epoxy adhesives. Not everything has been used on the materials that were chosen for this report, but there are a few connections which can be compared. Table 27 shows the result from two studies, one which researched the ultrasonic welding of PA to metals, with an adhesive reference on aluminium and PA, and the other did research on adhering epoxy based composites to steel.

Combination	Ultrasonic welding (MPa)	Epoxy adhesives (MPa)	Chosen adhesives (MPa)
Steel - PP	X	X	11.2
Aluminium - PP	X	X	6.8
Steel - PA	8.0 [8]	X	12.6
Aluminium - PA	11.0 / 16.5* [8]	20.5** [8]	7.8
Steel-Epoxy	X	23.98 [36]	X

*** Aluminium was etched with nitric acid**
**** Aluminium was etched with nitric acid and PA was treated with UV/ozone**

Table 27: Single lap shear strength comparison

The data from Table 27 shows that the epoxy adhesives are capable of reaching lap shear strengths which are twice as high as the strengths that were reached using the chosen adhesives. The difference between these two connections is that the aluminium-PA connection with epoxy adhesive was pre-treated in a different way. The PA surface was exposed to UV/ozone for 5 minutes to enhance the bonding properties, and the aluminium was grit blasted and etched with nitric acid. It could be that these surface treatments would also enhance the strength of the bond with the methacrylate adhesive, DP-8005. A steel-epoxy connection was researched by S. Ariaee et al. [36] with the use of an epoxy adhesive. This adhesive showed a strength which was higher than any of the other adhesives could achieve, but the epoxy adhesive on aluminium and PA did come close.

The ultrasonic welding showed a lower strength for steel-PA in comparison to the cyanoacrylate adhesive, but the bond of aluminium to PA shows a higher strength, compared to the methacrylate adhesive. The ultrasonic weld increased in strength when the aluminium was pre-treated using nitric acid. The usage of nitric acid was not tested for the adhesive connection of aluminium to PA.

The comparison of the results show that the lap shear strengths found with the fast curing adhesives are not bad. They exceed the strength of ultrasonic welding of steel to PA and the adhesives are only a little bit weaker for the connection of aluminium to PA. There was however no data available to compare the connection of PP to metal. The comparison of PA also showed that the strength, that is achieved with the fast curing adhesives, is not nearly as strong as connections that could be achieved using epoxy based adhesives. The only downside with these adhesives is that they require long curing times, which sometimes have to occur at elevated temperatures. So overall, the adhesives that produced the highest lap shear strengths for the connections of metal to composite look promising.

14. Recommendations

There is still a lot of research required before adhesive connections between composites and metals can be applied in the automotive industry. It will require a more stable result from the lap shear tests to accurately predict the maximum shear stress that the adhesive can handle. This can be obtained by better controlling the thickness of the adhesive, by for example the use of glass beads, and having a better alignment of the substrates by first adhering plates of material to each other and then cutting the specimen from these plates. This will result in a more equal alignment of each specimen.

It could also be helpful to have a reference strength for each adhesive on a connection between only the metals or composites. This could show give a better indication if the failure is related to the maximum shear stress that can be achieved on one of the materials. Some of this data was already provided in the data sheets of the adhesives, but not for every connection.

It would be of great benefit if the glass beads could be pre-mixed with the adhesives of Ruplo Lijmtechniek. This way the adhesive thickness will be easier to control with these adhesives. This is however currently not yet possible, because the glass beads start a reaction within the bottle. Drying of the glass beads does not prevent this, but maybe it is possible to coat the glass beads with a non-reactive layer or to replace the glass beads by another material. Also the effect of the activator on the adhesive strength should be tested. The activator is able to quickly cure thick layers of adhesive so that the time to handle is reduced, but it is unknown if this will also affect the strength of the adhesive.

Additional lap shear tests should be performed using other surface treatments to find out if the strength of the adhesive can be increased and if the deviations can be minimized. There are a few possible treatments which have proven to be effective in increasing the surface energy of thermoplastic polymers. Flame treatment is the easiest to perform surface treatment which does not require expensive machines. The treatment only requires a propane blow torch and isopropanol. The surface that is going to be adhered should be shortly exposed to the flame of the blow torch and cleaned afterwards with isopropanol. Acid etching of aluminium also showed promising results for the connection of aluminium to composites [8]. Cleaning the aluminium with bicarbonate at a temperature of 30°C could also be used to increase the bonding strength to aluminium, according to Ruplo Lijmtechniek [20].

An important thing that needs to be checked is the durability at high and low temperatures, depending on the application of the adhesive. The adhesives will probably be more brittle under cold conditions and could fail at a lower load. Not only the temperature has influence on the adhesive but also moisture will have effect on it as some adhesives tend to absorb moisture. Other testing methods could also be required, depending on the application of the adhesive, like for example a peel test or an impact test.

For further research, it would been easier to qualify an adhesive if there was a load case to which the adhesive had to fulfil. This way there can be some cooperation with the adhesive manufacturer to optimize the adhesive and get the best connection possible. Cooperation with the adhesive manufacturer could produce a more successful adhesive, which was unfortunately not the case with the adhesives made for the connection of PA to aluminium. However, this was only one of the modified adhesives that was tested. Other variations could give better results. A different approach in increasing the strength of the adhesive bonding could be to modify the composite material for better bonding, by for example experimenting with different release agents. This way the material could be optimized for bonding with certain types of adhesives.

15. Sources

[1] Koch, B., Knözinger, G., Pleschke, T., Wolf, H J., 'Hybid-Frontend als Strukturbauteil' (A hybrid front-end as a structural part), KU Kunststoffe Magazine, Carl Hanser Verlag, München, March 1999, p82-86.

[2] Droste, D., Naughton, P., Bowser, B., Röttger J., Burr, S., Imam, O., Zeitler, M., Heuft, T., Cawley, A., 'Bonded metal-plastic composite structures', SPE Automotive Composite Conference, Sept. 9-10, 2003.

[3] Parker, B.M., 'Adhesive bonding of fibre-reinforced composites', International Journal of Adhesion & Adhesives Vol. 14 No. 2 April 1994.

[4] Chongchen, X., Karthik, R., Ganesan, K., 'Thermoplastic adhesive bonding of galvanized steel to polypropylene composite and its durability', International Journal of Adhesion & Adhesives 22 (2002) 187-195, Oct. 8 2001.

[5] German, R., Sangeeta, G., 'Manufacturing and mechanical properties of thermoplastic hybrid laminates based on DP500 steel', Composites: Part A 40 (2009) 176-183, Oct. 29 2008.

[6] Yousuke Kawahito, Yusuke Niwa & Seiji Katayama (2014) Laser direct joining between stainless steel and polyethylene terephthalate plastic and reliability evaluation of joints, Welding International, 28:2, 107-113, DOI: 10.1080/09507116.2012.715883.

[7] Mitschang, P., Velthuis, R., Didi, M., 'Induction spot welding of metal/CFRPC hybrid joints', Advanced engineering materials 2013, 15, No. 9.

[8] master thesis bolt

[9] Schierl A., 'The CMT process a revolution in welding technology', Weld world 2005, 49(9):38.

[10] Guild, F.J., Hogg, P.J., Tu, W., 'Comeld™ joints: a novel technique for bonding composites and metals', School of engineering and material science.

[11] Ucsnik, S., Scheerer, M., Zaremba, S., Pahr, D.H., 'Experimental investigation of a novel hybrid metal-composite joining technology', Composites: Part A 41 (2010) 369-374, Nov. 8 2009.

[12] NASA, 'Fasteners of the future', Oct. 2011, http://www.nasa.gov/centers/dryden/news/X-Press/aerovations/2011/fasteners_of_the_future_prt.htm

[13] Permabond, 'Composite bonding', 1999, http://www.compositesuk.co.uk/LinkClick.aspx?fileticket=wqdp3QzdVvA%3D&tabid=104&mid=511.

[14] DSM Engineering plastics, 'Gluing guide', http://www.dsm.com/content/dam/dsm/automotive/en_US/documents/gluing-guide.pdf.

[15] Huntsman Advanced Materials, 'Adhesives selector guide', www.huntsman.com/advanced_materials.

[16] 3M, 'Product catalogue', http://www.3m.com/.

[17] Huntsman Advanced Materials, 'Araldite® 2021 Technical Data Sheet', http://www.intertronics.co.uk/data/ara2021.pdf.

[18] Henkel, ‘Loctite® 4090 Technical Data Sheet’, http://www.henkel-adhesives.com.ph/product-search-1284.htm?nodeid=8803629694977.

[19] 3M, ‘Scotch-Weld™ Structural Plastic Adhesive DP-8005 Technical Data Sheet’, http://solutions.3m.com.au/3MContentRetrievalAPI/BlobServlet?lmd=1317022385000&locale=en_AU&assetType=MMM_Image&assetId=1273695674731&blobAttribute=ImageFile.

[20] Ruplo Lijmtechniek, Adhesive solutions, http://ruplo.nl.

[21] Lines, C., ‘Solving the problem of adhesion to plastics & rubber’, Dyne Technology, http://dynetechnology.co.uk/pdfs/bondingtoplasticandrubber.pdfn.

[22] A.M. Guedes Pinto, A.G. Magalhães, F. Gomes da Silva, A.P. Monteiro Baptista, ‘Shear strength of adhesively bonded polyolefins with minimal surface preparation’, International Journal of Adhesion & Adhesives 28 (2008) 452-456, April. 10 2008.

[23] Molitor, P., Barron, V., Young, T., ‘Surface treatment of titanium for adhesive bondig to polymer composites: a review’, International Journal of Adhesion & Adhesives 21 (2001) 129-136, July 3 2000.

[24] Kinloch, A.J., ‘Adhesion and adhesives’, London: Chapman & Hall, 1987, 115-145.

[25] Rohde Technics, ‘Surface treatment, Grit blasting’, http://www.rohde-technics.de/

[26] P. Blais, D. J. Carlsson, G. W. Csullog, D. M. Wiles, ‘The chromic acid etching of polyolefin surfaces and adhesive bonding’, Yonrual of Colloid and Interface Science, Vol. 47, No. 3, June 1974.

[27] Comyn, J., Mascia, L., Xiao, G., ‘Corona-discharge treatment of polyetheretherketone (PEEK) for adhesive bonding’, International Journal Adhesion Adhesives 1996, 301-304.

[28] Intertronics, ‘Corona surface treatments’, http://www.intertronics.co.uk/.

[29] Baalmann, A., Vissing, K.D., Born, E., Gross, A., ‘Surface treatment of polyetheretherketone (PEEK) composites by plasma activation’, International Journal Adhesion Adhesives 1994.

[30] Scanteco, ‘Flame treating’, http://scanteco.dk /.

[31] Sina Ebnesajjad,Cyrus Ebnesajjad, ‘Surface treatment of materials for adhesive bonding’, Elsevier, 2014, 163.

[32] ASTM D5868-01, ‘Standard for lap shear test between composite and metals’.

[33] Klein, B., ‘Leichtbau Konstruktion’, Germany: Vieweg+Teubner, 296-307.

[34] AdhesivesToolkit, ‘Adhesive desing toolkit’, http://www.adhesivestoolkit.com/.

[35] FDP, ‘Lijmprocessen voor dunne plaat en buis’, Tech-Info-blad, nr. TI.03.15, mei 2003.

[36] Ariaee, S., Tutunchi, A., Kianvash, A., Entezami, A., ‘Modeling and optimization of mechanical behaviour of bonded composite-steel single lap joints by response surface methodology’, International Journal of Adhesion & Adhesives 54 (2014) 30-39, April. 20 2014.

16. APPENDIX A

The next few pages will show the individual results of each of the lap shear tests that were performed.

Zwick, type: Z1474

Ten Cate Advanced Composites

Lap shear properties

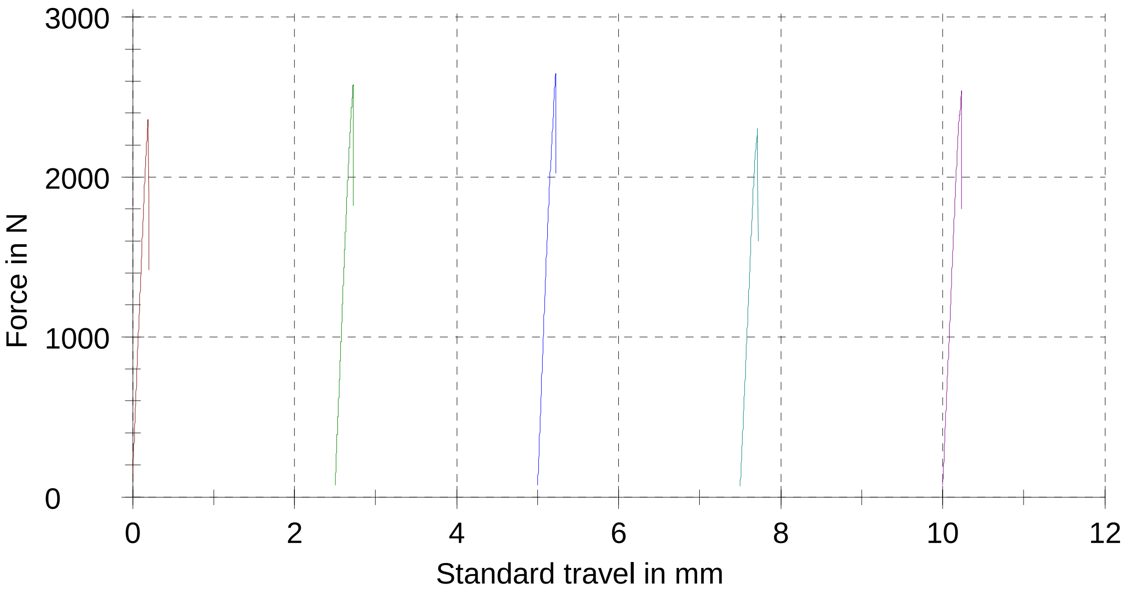
Test parameters for testbatch:

Name operator	:	Marco van Oosten
Substrate 1	:	Steel
Substrate 2	:	PA
Adhesive	:	Araldite 2021
Pre-conditioning	:	-
Test condition	:	23 °C / 50% RH

Date	:	11-12-2014
Test standard	:	ASTM-D5868
Test type	:	Lap Shear
Grips	:	F-0693
Test speed	:	13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	17	2361	4,0	0,20	NS
	2	19	2575	4,2	0,22	NS
	3	20	2649	4,4	0,23	NS
	4	21	2303	3,8	0,22	NS
	5	22	2538	4,2	0,24	NS
	✝6	23	1260	2,1	0,11	NS
	✝7	24	1052	1,7	0,09	NS



Statistics:

n = 5	Fmax N	τmax MPa	smax mm
$\bar{x}$	2485	4,1	0,22
s	147	0,2	0,01
ν	5,91	5,21	6,15

Ten Cate Advanced Composites

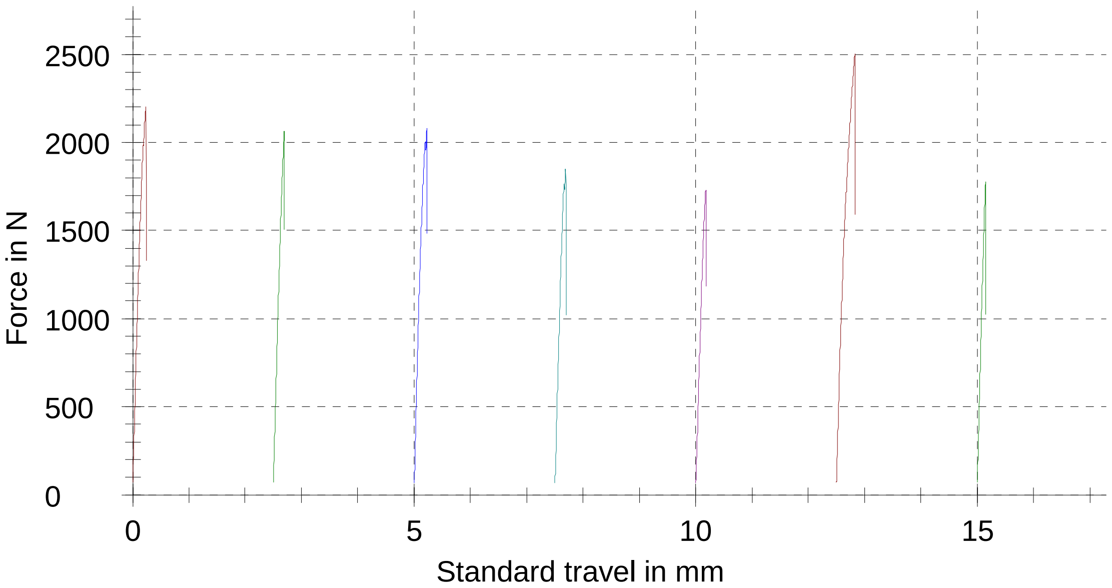
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	12-12-2014
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Araldite 2021	Grips	:	F-0693
Pre-conditioning	:	168 Hrs. @ 85°C	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	33	2201	3,4	0,24	NS
	2	34	2065	3,4	0,20	NS
	3	35	2082	3,4	0,23	NS
	4	36	1848	2,9	0,20	NS
	5	38	1728	2,8	0,19	NS
	6	39	2501	4,0	0,34	NS
	7	40	1777	2,8	0,16	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	2029	3,3	0,22
s	272	0,4	0,06
ν	13,40	13,52	26,10

Ten Cate Advanced Composites

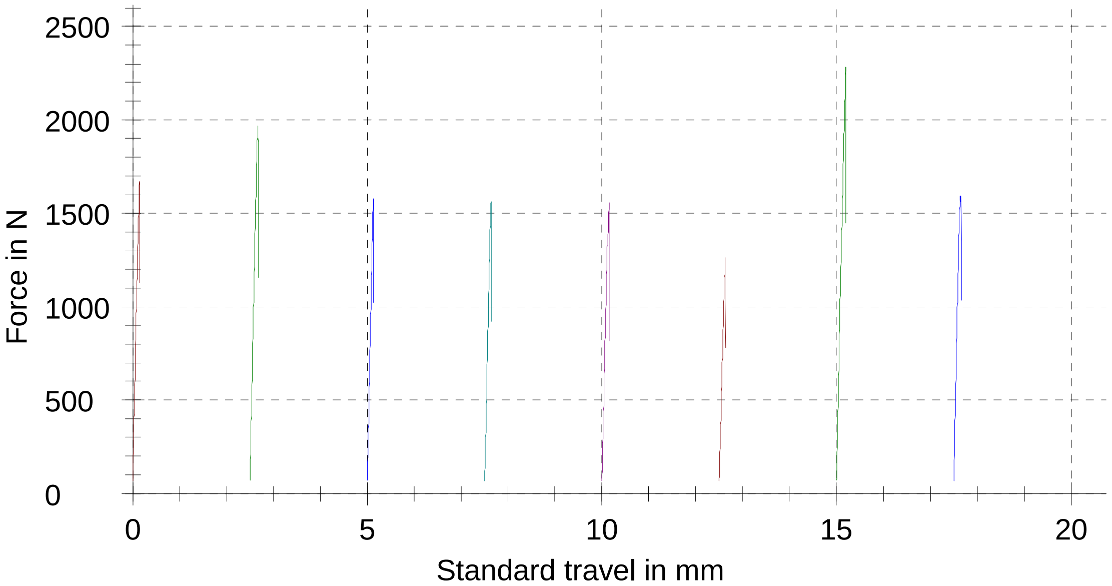
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	11-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Araldite 2021	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	25	1672	2,8	0,15	NS
	2	26	1968	3,2	0,18	NS
	3	27	1577	2,7	0,14	NS
	4	28	1561	2,5	0,15	NS
	5	29	1559	2,5	0,17	NS
	6	30	1263	2,2	0,13	NS
	7	31	2282	3,8	0,20	NS
	8	32	1595	2,6	0,16	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	1684	2,8	0,16
s	308	0,5	0,02
ν	18,31	17,87	14,18

Ten Cate Advanced Composites

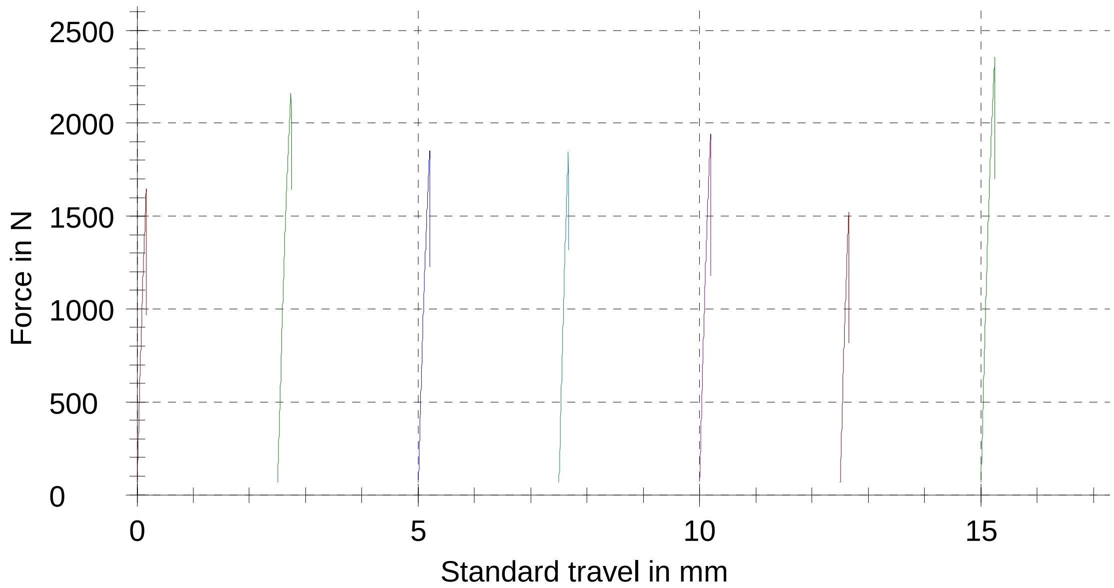
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	12-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Araldite 2021	Grips	:	F-0693
Pre-conditioning	:	168 Hrs @ 85°C	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	42	1649	2,7	0,17	NS
	2	43	2160	3,6	0,24	NS
	3	44	1852	2,9	0,21	NS
	4	45	1845	2,9	0,17	NS
	5	46	1940	3,1	0,20	NS
	6	47	1522	2,5	0,16	NS
	7	48	2356	3,7	0,25	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	1903	3,1	0,20
s	285	0,5	0,04
ν	14,99	14,75	18,39

Ten Cate Advanced Composites

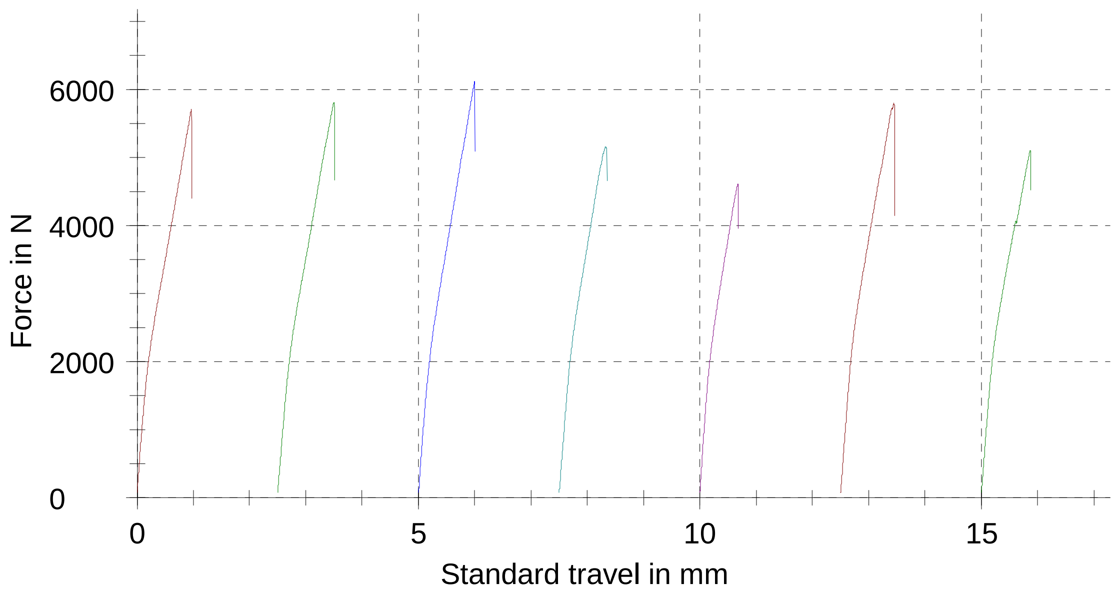
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	12-12-2014
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PP	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15-1	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	1	5709	8,9	0,97	NS
	2	2	5812	9,3	1,01	NS
	3	3	6115	9,7	1,00	NS
	4	4	5158	8,2	0,85	NS
	5	5	4607	7,4	0,68	NS
	6	6	5794	9,3	0,96	NS
	7	7	5100	8,2	0,88	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	5471	8,7	0,91
s	528	0,8	0,12
ν	9,65	9,38	12,88

Ten Cate Advanced Composites

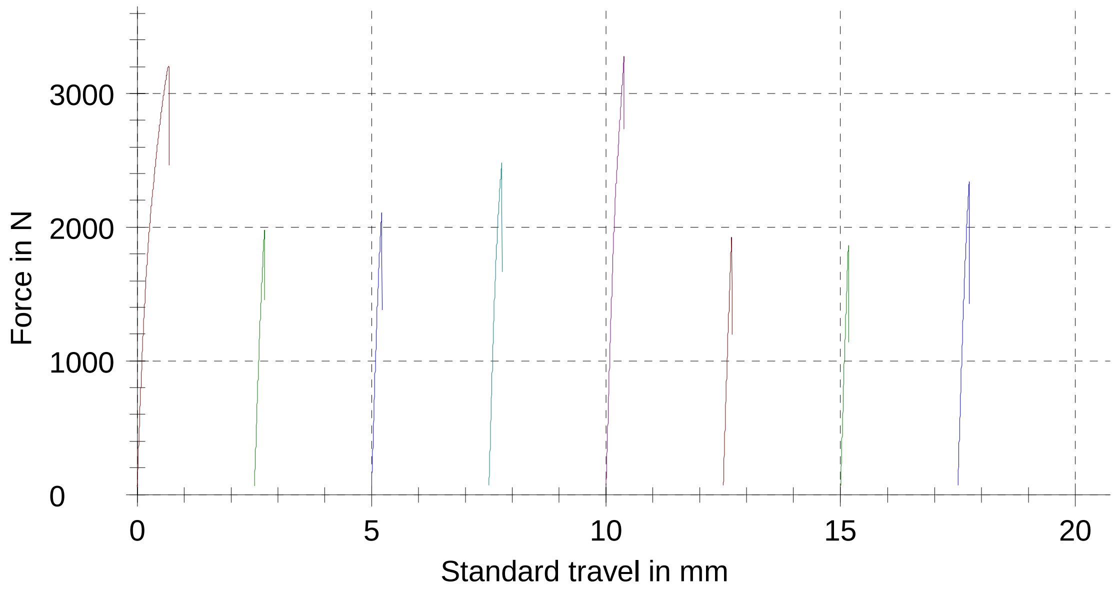
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	12-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PP	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15-1	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	9	3205	5,1	0,69	NS
	2	10	1979	3,1	0,22	NS
	3	11	2109	3,3	0,22	NS
	4	12	2479	4,0	0,28	NS
	5	13	3277	5,2	0,39	NS
	6	14	1925	3,0	0,18	NS
	7	15	1865	3,0	0,17	NS
	8	16	2341	3,7	0,25	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	2398	3,8	0,30
s	561	0,9	0,17
ν	23,38	23,29	56,90

Ten Cate Advanced Composites

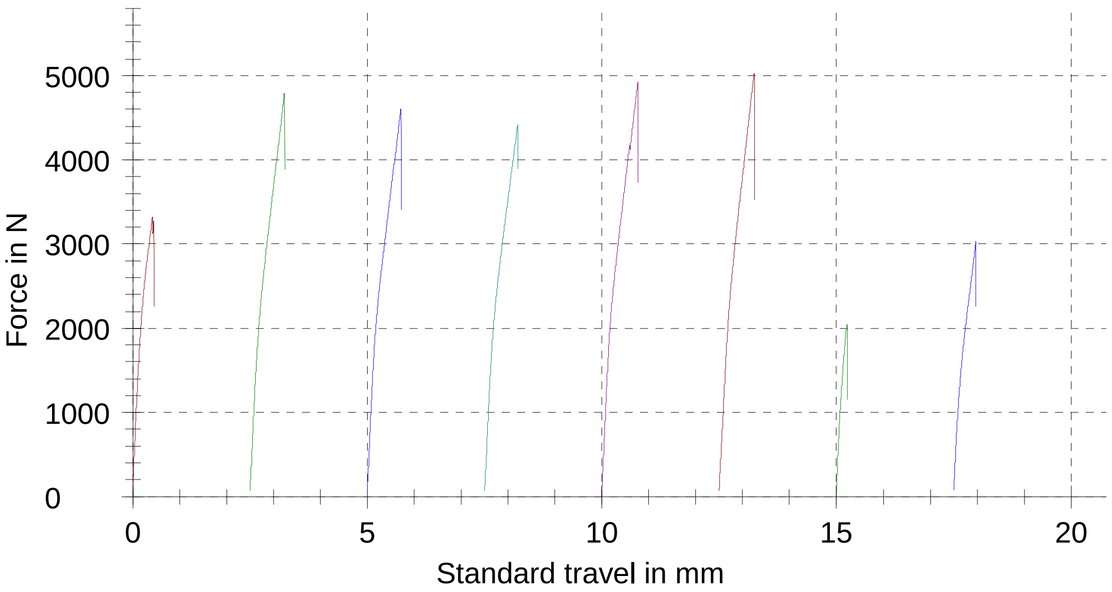
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	12-12-2014
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15-1	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	17	3321	5,3	0,45	NS
	2	18	4792	7,7	0,74	NS
	3	19	4602	7,3	0,72	NS
	4	20	4410	7,0	0,71	NS
	5	21	4929	7,9	0,78	NS
	6	22	5022	7,8	0,75	NS
	7	23	2047	3,3	0,23	NS
	8	24	3030	4,8	0,48	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\overline{x}$	4019	6,4	0,61
s	1088	1,7	0,20
ν	27,06	26,87	32,40

Ten Cate Advanced Composites

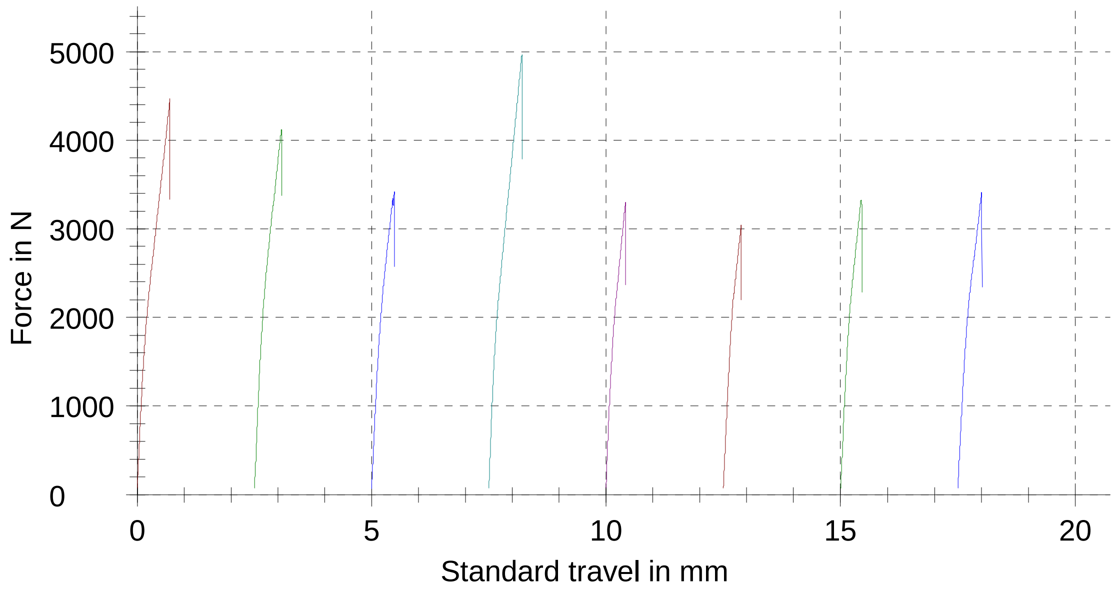
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	17-12-2014
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15-1	Grips	:	F-0693
Pre-conditioning	:	168 Hrs @ 85°C	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	35	4471	7,1	0,71	NS
	2	36	4121	6,5	0,58	NS
	3	37	3421	5,5	0,49	NS
	4	38	4963	7,9	0,71	NS
	5	39	3296	5,2	0,42	NS
	6	40	3042	4,8	0,39	NS
	7	41	3324	5,4	0,46	NS
	8	42	3413	5,4	0,51	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	3756	6,0	0,53
s	680	1,1	0,12
ν	18,11	18,02	22,91

Ten Cate Advanced Composites

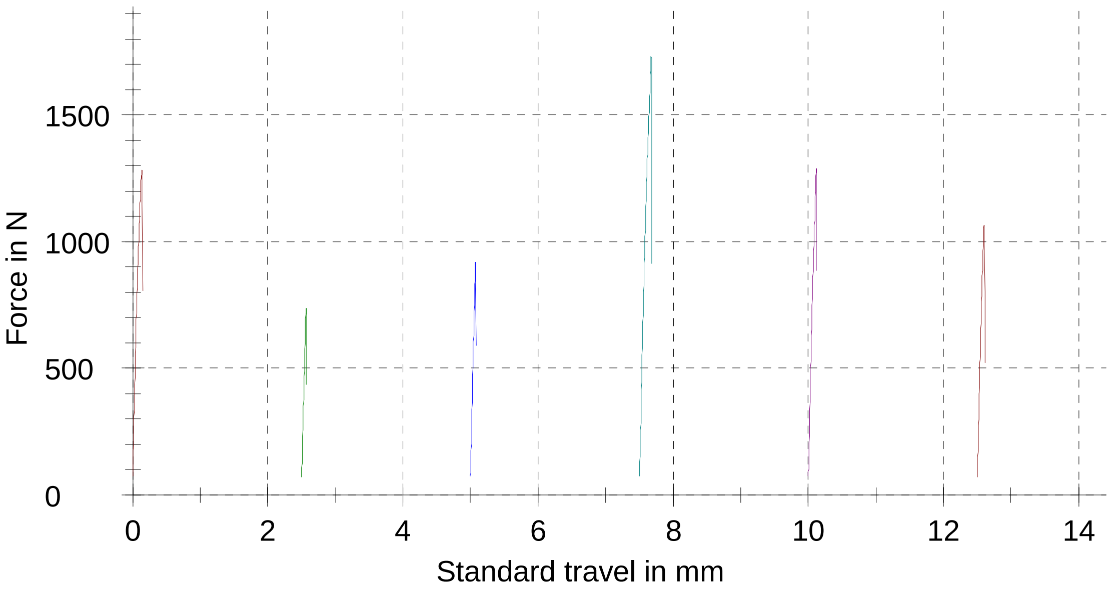
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	16-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15-1	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	26	1283	2,0	0,15	NS
	2	27	735	1,2	0,07	NS
	3	28	918	1,4	0,08	NS
	4	31	1729	2,7	0,18	NS
	5	32	1289	2,1	0,12	NS
	6	33	1064	1,7	0,11	NS



Statistics:

n = 6	Fmax N	τmax MPa	smax mm
$\overline{x}$	1170	1,9	0,12
s	347	0,5	0,04
ν	29,70	29,42	34,42

Ten Cate Advanced Composites

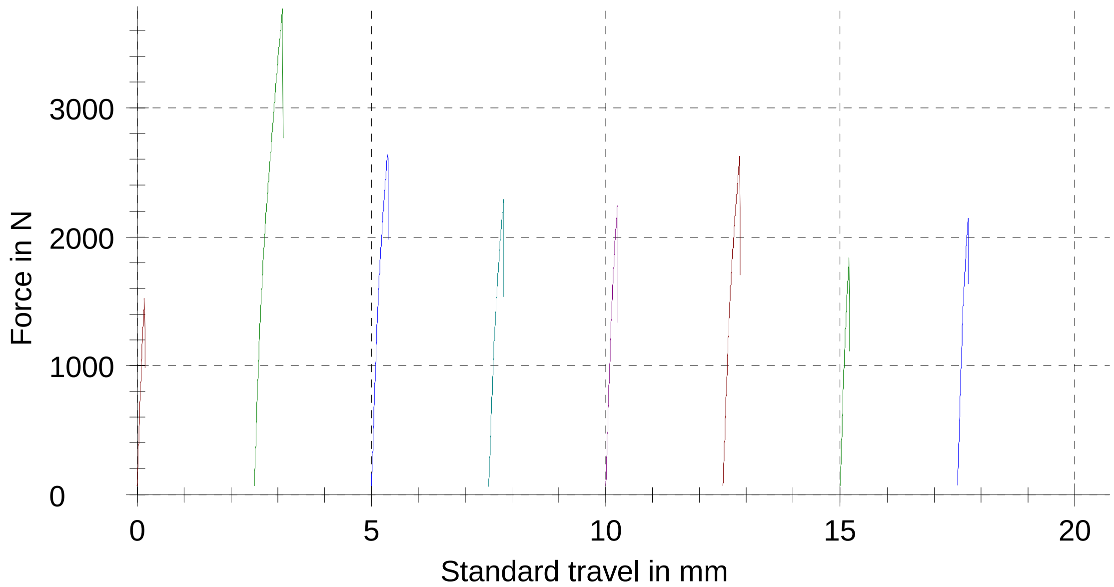
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	17-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15-1	Grips	:	F-0693
Pre-conditioning	:	168 Hrs @ 85°C	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	43	1522	2,4	0,16	NS
	2	44	3771	6,1	0,61	NS
	3	45	2636	4,3	0,36	NS
	4	46	2293	3,7	0,33	NS
	5	47	2246	3,6	0,26	NS
	6	48	2626	4,2	0,36	NS
	7	49	1840	3,0	0,20	NS
	8	50	2145	3,4	0,24	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	2385	3,8	0,31
s	673	1,1	0,14
ν	28,22	28,45	44,81

Ten Cate Advanced Composites

Lap shear properties

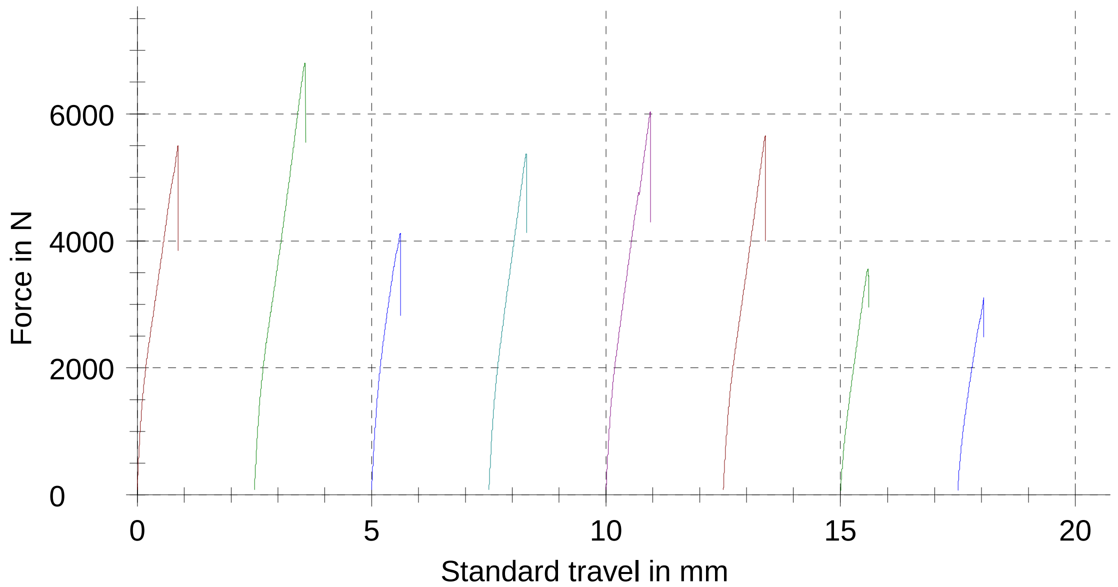
Test parameters for testbatch:

Name operator : Marco van Oosten
Substrate 1 : Steel
Substrate 2 : PP
Adhesive : Cyanoacrylate 1500 V-AM-15
Pre-conditioning : -
Test condition : 23 °C / 50% RH

Date : 17-12-2014
Test standard : ASTM-D5868
Test type : Lap Shear
Grips : F-0693
Test speed : 13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	1	5496	8,7	0,88	NS
	2	2	6798	10,8	1,09	NS
	3	3	4115	6,6	0,61	NS
	4	4	5366	8,6	0,81	NS
	5	5	6038	9,6	0,95	NS
	6	6	5653	9,0	0,90	NS
	7	7	3557	5,7	0,60	NS
	8	8	3109	4,9	0,56	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	5017	8,0	0,80
s	1285	2,1	0,19
ν	25,61	25,85	23,86

Zwick, type: Z1474

Ten Cate Advanced Composites

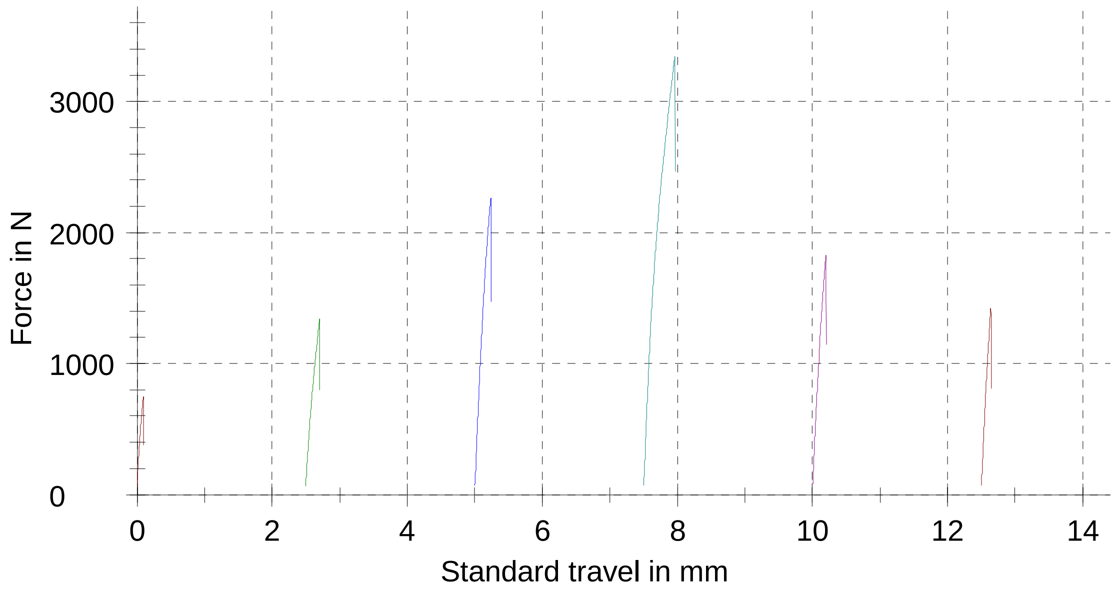
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten
Substrate 1	:	Aluminium
Substrate 2	:	PP
Adhesive	:	Cyanoacrylate 1500 V-AM-15
Pre-conditioning	:	-
Test condition	:	23 °C / 50% RH
Date	:	17-12-2014
Test standard	:	ASTM-D5868
Test type	:	Lap Shear
Grips	:	F-0693
Test speed	:	13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	10	747	1,2	0,10	NS
	2	11	1341	2,1	0,21	NS
	3	12	2261	3,6	0,24	NS
	4	13	3341	5,3	0,47	NS
	5	15	1825	2,9	0,21	NS
	6	16	1423	2,3	0,15	NS



Statistics:

n = 6	Fmax N	τmax MPa	smax mm
$\bar{x}$	1823	2,9	0,23
s	900	1,4	0,13
ν	49,36	48,60	56,25

Zwick, type: Z1474

Ten Cate Advanced Composites

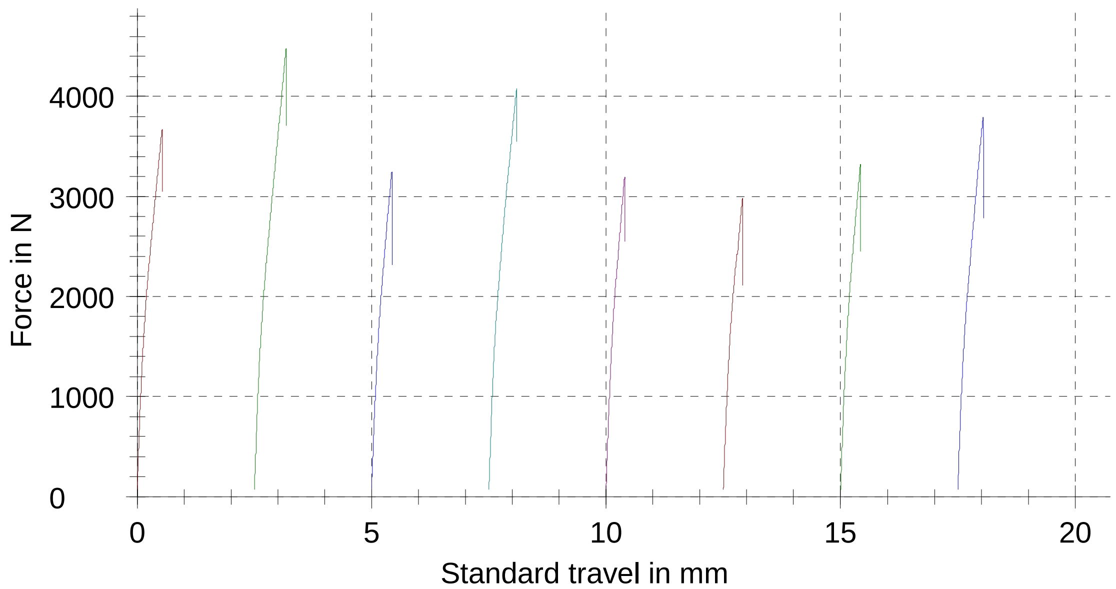
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	19-12-2014
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	17	3666	5,9	0,53	NS
	2	18	4478	7,1	0,68	NS
	3	19	3249	5,2	0,43	NS
	4	20	4074	6,6	0,59	NS
	5	21	3191	5,2	0,40	NS
	6	22	2979	4,7	0,41	NS
	7	23	3322	5,4	0,43	NS
	8	24	3793	6,0	0,55	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	3594	5,8	0,50
s	506	0,8	0,10
ν	14,07	13,90	20,02

Ten Cate Advanced Composites

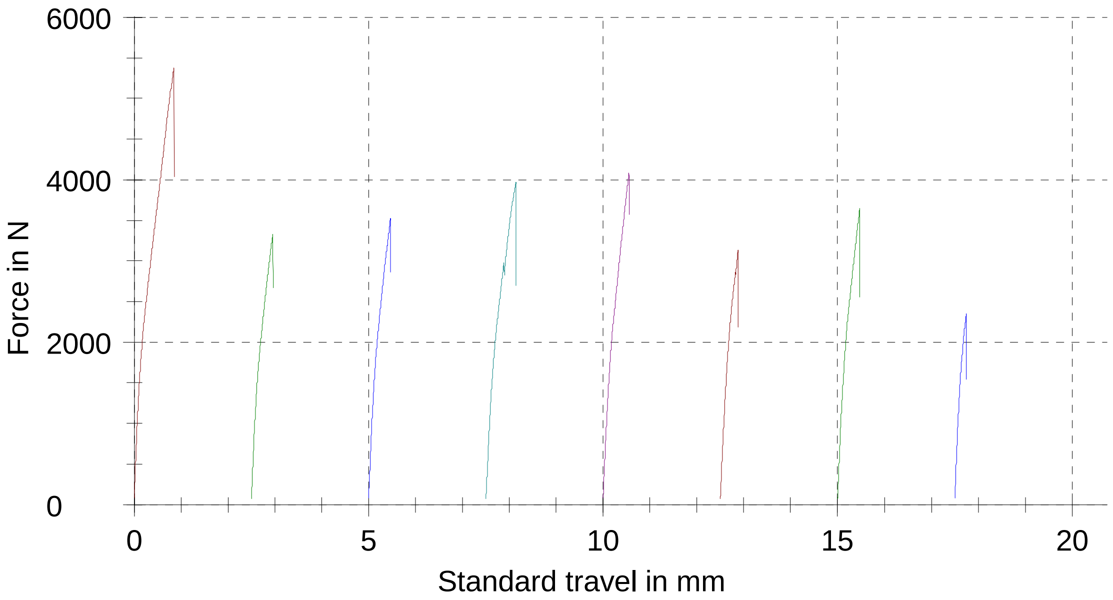
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	19-12-2014
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15	Grips	:	F-0693
Pre-conditioning	:	168 Hrs @ 85°C	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	35	5380	8,4	0,85	NS
	2	36	3333	5,3	0,47	NS
	3	37	3520	5,6	0,47	NS
	4	38	3974	6,3	0,65	NS
	5	39	4084	6,4	0,56	NS
	6	40	3136	5,0	0,38	NS
	7	41	3641	5,7	0,48	NS
	8	42	2350	3,7	0,25	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	3677	5,8	0,51
s	874	1,4	0,18
ν	23,78	23,40	35,06

Ten Cate Advanced Composites

Lap shear properties

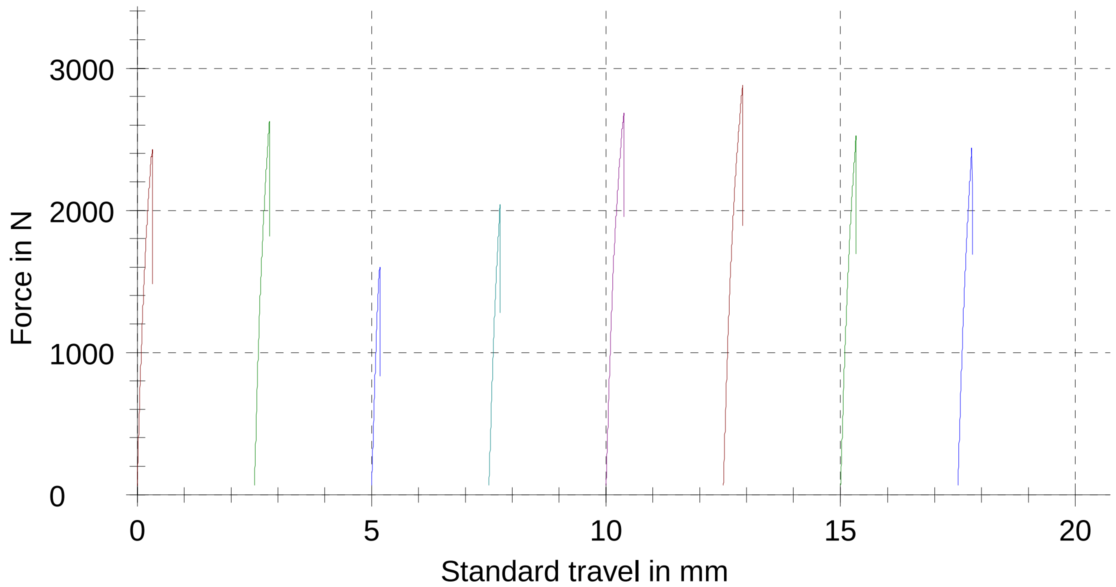
Test parameters for testbatch:

Name operator	:	Marco van Oosten
Substrate 1	:	Aluminium
Substrate 2	:	PA
Adhesive	:	Cyanoacrylate 1500 V-AM-15
Pre-conditioning	:	-
Test condition	:	23 °C / 50% RH

Date	:	19-12-2014
Test standard	:	ASTM-D5868
Test type	:	Lap Shear
Grips	:	F-0693
Test speed	:	13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	26	2428	3,8	0,34	NS
	2	27	2625	4,2	0,32	NS
	3	28	1600	2,5	0,18	NS
	4	29	2038	3,2	0,24	NS
	5	30	2683	4,3	0,39	NS
	6	31	2882	4,6	0,42	NS
	7	32	2525	4,0	0,33	NS
	8	33	2441	3,8	0,31	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\overline{x}$	2403	3,8	0,32
s	406	0,7	0,07
ν	16,88	17,14	23,61

Ten Cate Advanced Composites

Lap shear properties

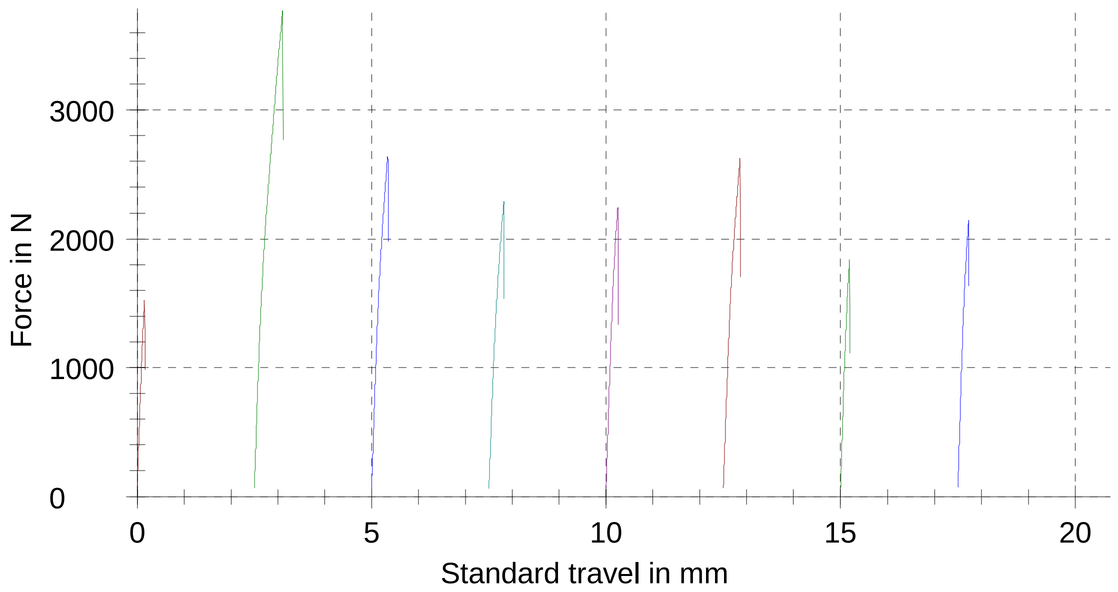
Test parameters for testbatch:

Name operator	:	Marco van Oosten
Substrate 1	:	Aluminium
Substrate 2	:	PA
Adhesive	:	Cyanoacrylate 1500 V-AM-15-1
Pre-conditioning	:	168 Hrs @ 85°C
Test condition	:	23 °C / 50% RH

Date	:	17-12-2014
Test standard	:	ASTM-D5868
Test type	:	Lap Shear
Grips	:	F-0693
Test speed	:	13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	43	1522	2,4	0,16	NS
	2	44	3771	6,1	0,61	NS
	3	45	2636	4,3	0,36	NS
	4	46	2293	3,7	0,33	NS
	5	47	2246	3,6	0,26	NS
	6	48	2626	4,2	0,36	NS
	7	49	1840	3,0	0,20	NS
	8	50	2145	3,4	0,24	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\overline{x}$	2385	3,8	0,31
s	673	1,1	0,14
ν	28,22	28,45	44,81

Ten Cate Advanced Composites

Lap shear properties

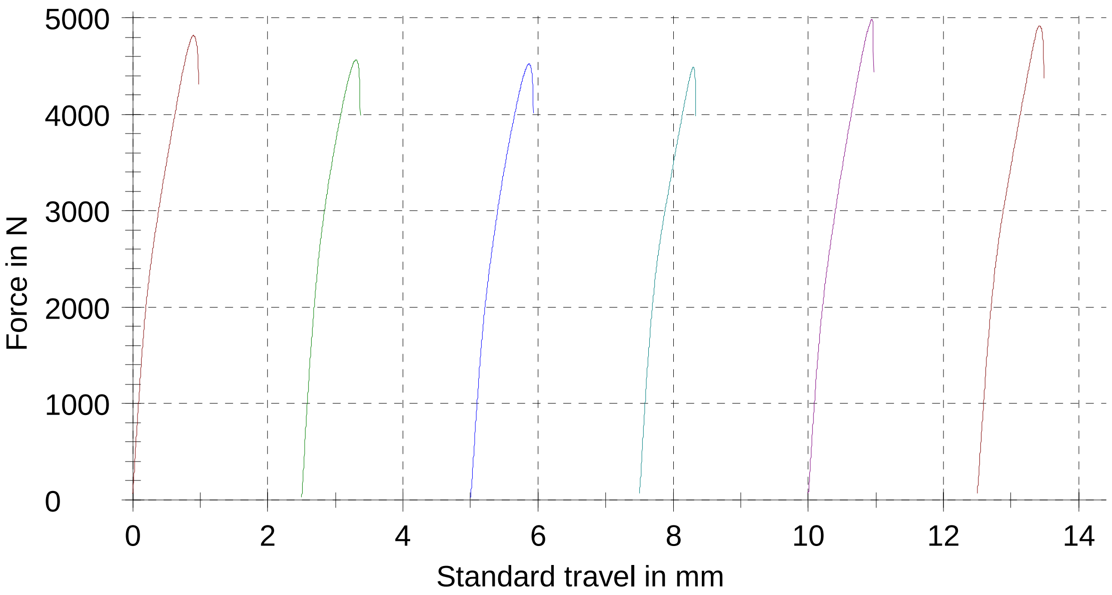
Test parameters for testbatch:

Name operator : Marco van Oosten
Substrate 1 : Steel
Substrate 2 : PP
Adhesive : DP-8005
Pre-conditioning : -
Test condition : 23 °C / 50% RH

Date : 16-12-2014
Test standard : ASTM-D5868
Test type : Lap Shear
Grips : F-0693
Test speed : 13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	1	4817	7,5	0,98	NS
	2	2	4563	7,3	0,87	NS
	3	3	4523	7,3	0,93	NS
	4	4	4488	7,0	0,83	NS
	5	5	4981	7,8	0,97	NS
	6	6	4914	7,9	0,99	NS



Statistics:

n = 6	Fmax N	τmax MPa	smax mm
$\bar{x}$	4714	7,5	0,93
s	215	0,3	0,06
ν	4,57	4,49	6,81

Ten Cate Advanced Composites

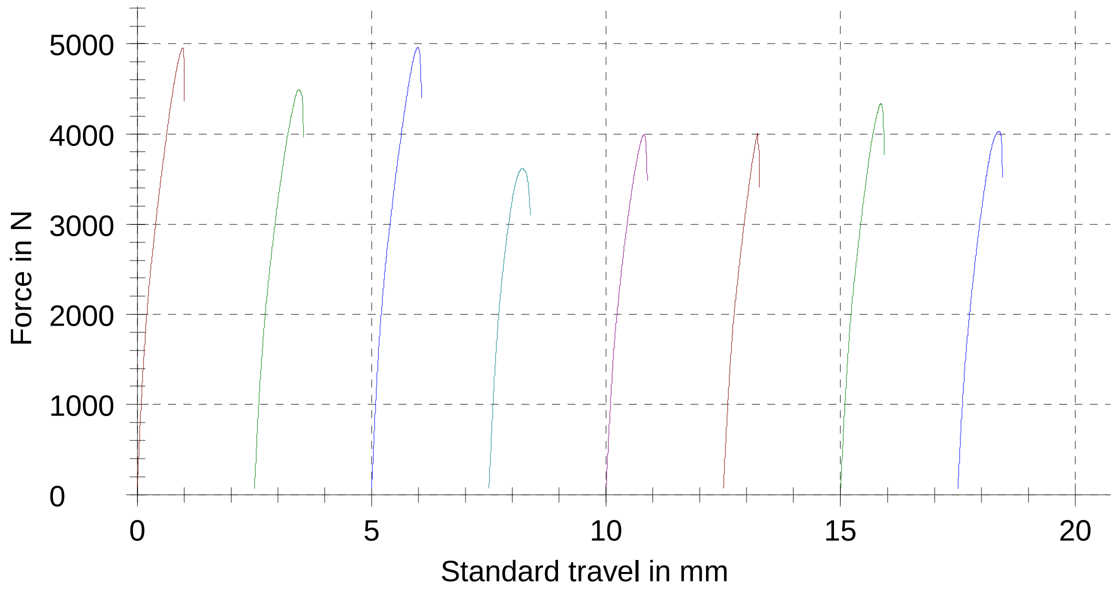
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	16-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PP	Test type	:	Lap Shear
Adhesive	:	DP-8005	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	10	4955	7,8	1,01	NS
	2	11	4490	7,4	1,05	NS
	3	12	4962	7,6	1,06	NS
	4	13	3619	5,8	0,88	NS
	5	14	3990	6,2	0,88	NS
	6	15	4009	6,3	0,78	NS
	7	16	4337	6,9	0,92	NS
	8	17	4026	6,3	0,95	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	4299	6,8	0,94
s	481	0,7	0,10
ν	11,20	10,65	10,40

Ten Cate Advanced Composites

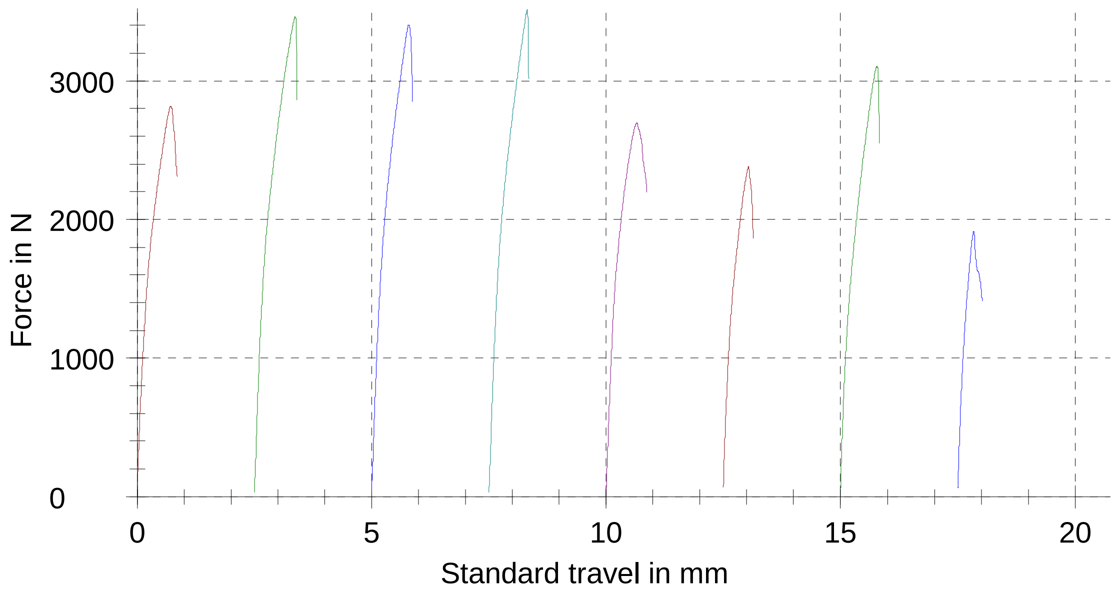
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	16-12-2014
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	DP-8005	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	19	2817	4,5	0,85	NS
	2	20	3462	5,6	0,91	NS
	3	21	3404	5,5	0,87	NS
	4	22	3516	5,6	0,85	NS
	5	23	2697	4,2	0,87	NS
	6	25	2384	3,8	0,64	NS
	7	25	3105	4,8	0,83	NS
	8	26	1913	3,1	0,52	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	2912	4,6	0,79
s	571	0,9	0,14
ν	19,60	19,68	17,32

Ten Cate Advanced Composites

Lap shear properties

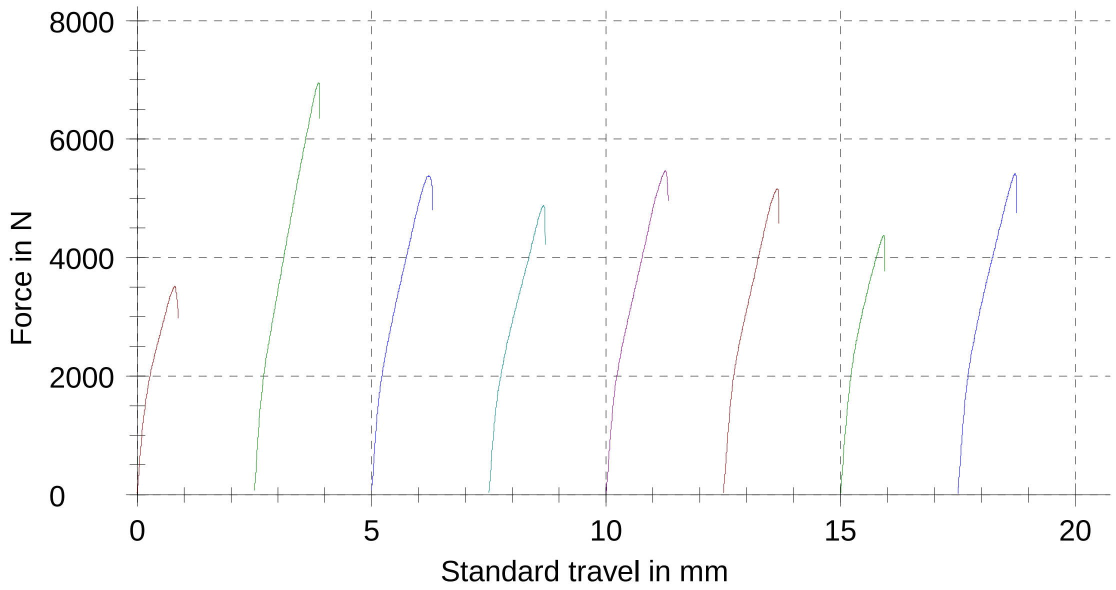
Test parameters for testbatch:

Name operator	:	Marco van Oosten
Substrate 1	:	Steel
Substrate 2	:	PA
Adhesive	:	DP-8005
Pre-conditioning	:	168 Hrs @ 85°C
Test condition	:	23 °C / 50% RH

Date	:	17-12-2014
Test standard	:	ASTM-D5868
Test type	:	Lap Shear
Grips	:	F-0693
Test speed	:	13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	39	3513	5,7	0,88	NS
	2	40	6952	11,0	1,40	NS
	3	41	5376	8,4	1,30	NS
	4	42	4881	7,8	1,20	NS
	5	43	5469	8,6	1,33	NS
	6	44	5166	8,3	1,18	NS
	7	45	4369	6,9	0,95	NS
	8	46	5413	8,3	1,25	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	5142	8,1	1,19
s	988	1,5	0,18
ν	19,21	18,75	15,34

Zwick, type: Z1474

Ten Cate Advanced Composites

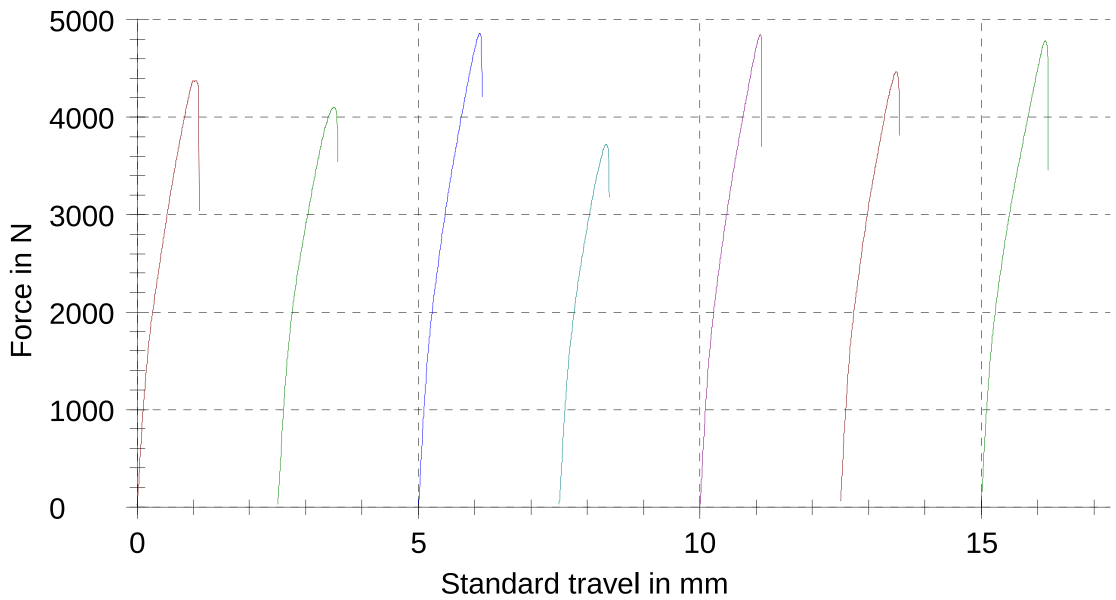
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	17-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	DP-8005	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	29	4376	6,9	1,10	NS
	2	30	4104	6,5	1,06	NS
	3	31	4859	7,7	1,13	NS
	4	32	3723	5,9	0,89	NS
	5	33	4848	7,6	1,10	NS
	6	34	4469	7,0	1,04	NS
	7	35	4783	7,7	1,18	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	4452	7,1	1,07
s	427	0,7	0,09
ν	9,58	9,87	8,57

Ten Cate Advanced Composites

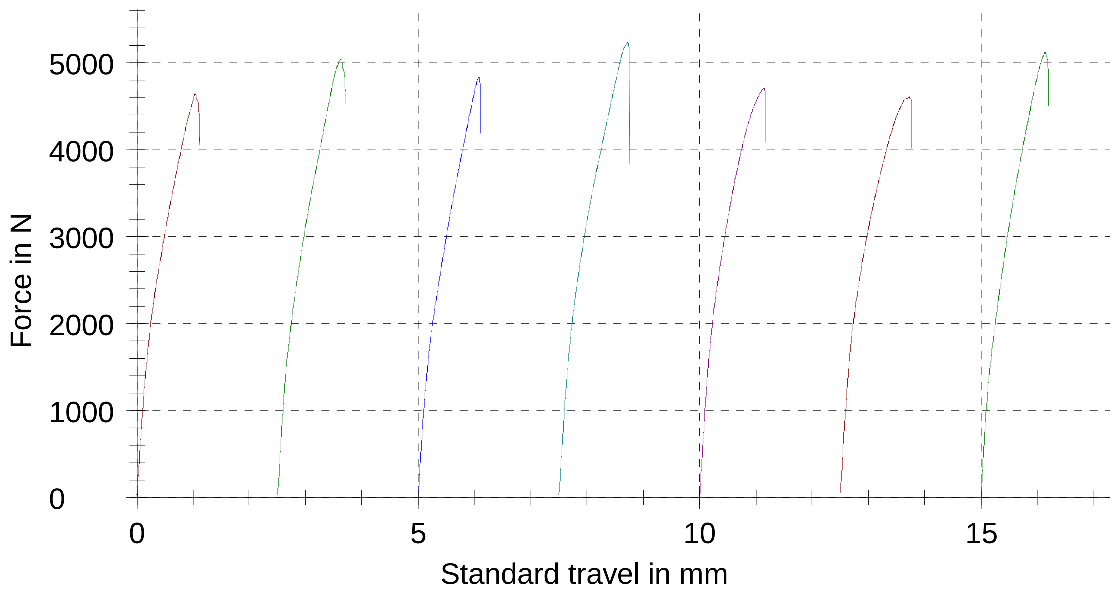
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	17-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	DP-8005	Grips	:	F-0693
Pre-conditioning	:	168 Hrs @ 85°C	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	47	4642	7,5	1,12	NS
	2	48	5044	7,9	1,21	NS
	3	49	4835	7,6	1,11	NS
	4	50	5231	8,4	1,26	NS
	5	51	4703	7,5	1,17	NS
	6	52	4607	7,3	1,27	NS
	7	53	5119	8,3	1,20	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	4883	7,8	1,19
s	249	0,4	0,06
ν	5,09	5,47	5,43

Ten Cate Advanced Composites

Lap shear properties

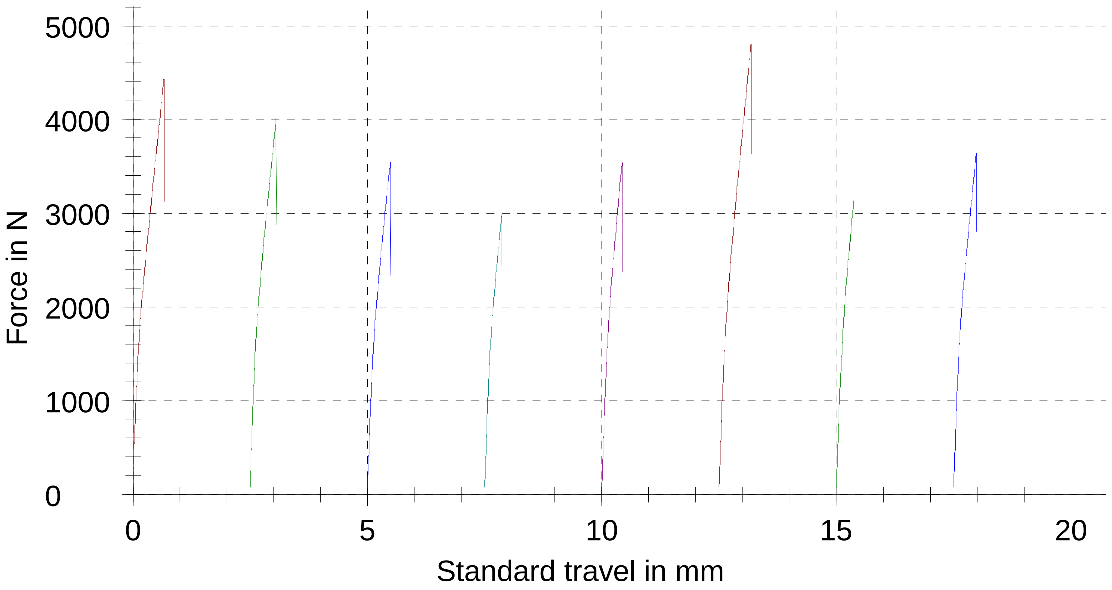
Test parameters for testbatch:

Name operator : Marco van Oosten
Substrate 1 : Steel
Substrate 2 : PP
Adhesive : Loctite 4090
Pre-conditioning : -
Test condition : 23 °C / 50% RH

Date : 18-12-2014
Test standard : ASTM-D5868
Test type : Lap Shear
Grips : F-0693
Test speed : 13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	1	4431	7,2	0,67	NS
	2	2	4010	6,4	0,56	NS
	3	3	3541	5,7	0,50	NS
	4	4	2992	4,8	0,37	NS
	5	5	3539	5,7	0,44	NS
	6	6	4807	7,6	0,68	NS
	7	7	3145	5,1	0,38	NS
	8	8	3639	5,9	0,49	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	3763	6,0	0,51
s	620	1,0	0,12
ν	16,47	15,97	23,36

Zwick, type: Z1474

Ten Cate Advanced Composites

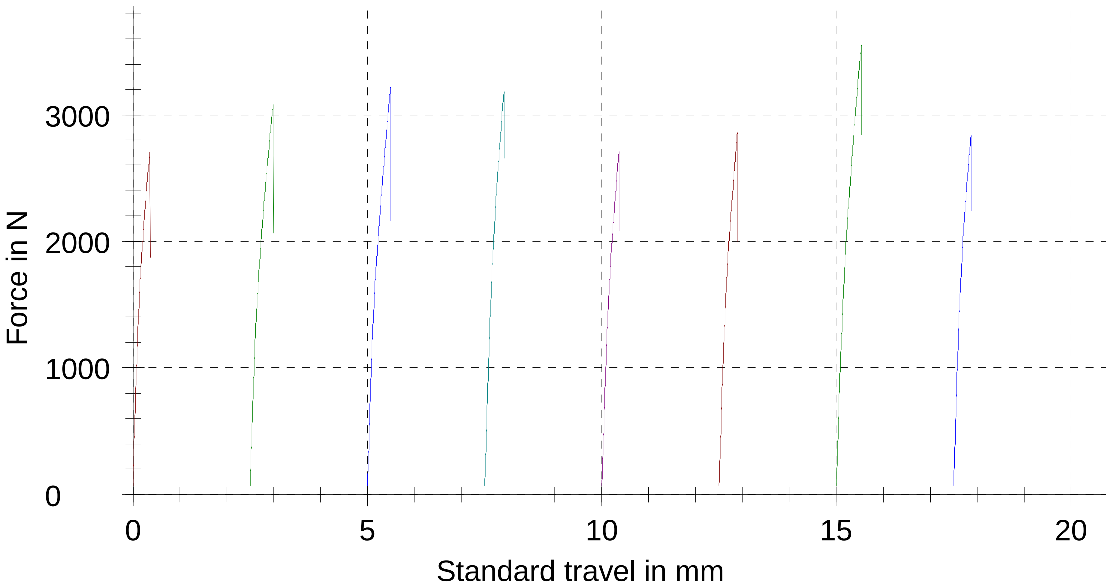
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	18-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PP	Test type	:	Lap Shear
Adhesive	:	Loctite 4090	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	9	2705	4,3	0,37	NS
	2	10	3081	5,0	0,50	NS
	3	11	3220	5,2	0,50	NS
	4	12	3184	5,1	0,42	NS
	5	13	2709	4,3	0,37	NS
	6	14	2858	4,6	0,40	NS
	7	15	3555	5,7	0,54	NS
	8	16	2834	4,7	0,38	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	3018	4,9	0,43
s	296	0,5	0,07
ν	9,81	9,69	15,62

Zwick, type: Z1474

Ten Cate Advanced Composites

Lap shear properties

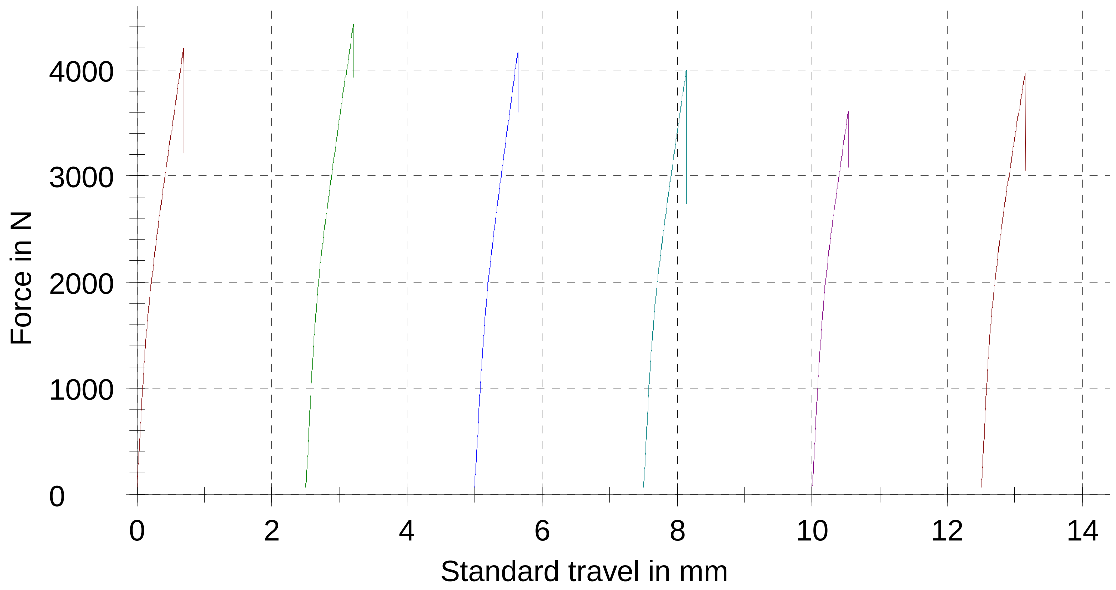
Test parameters for testbatch:

Name operator : Marco van Oosten
Substrate 1 : Steel
Substrate 2 : PA
Adhesive : Loctite 4090
Pre-conditioning : -
Test condition : 23 °C / 50% RH

Date : 18-12-2014
Test standard : ASTM-D5868
Test type : Lap Shear
Grips : F-0693
Test speed : 13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	17	4206	6,7	0,70	NS
	2	18	4429	7,1	0,71	NS
	3	19	4161	6,8	0,64	NS
	4	20	3997	6,2	0,64	NS
	5	21	3607	5,8	0,54	NS
	6	22	3970	6,5	0,66	NS



Statistics:

n = 6	Fmax N	τmax MPa	smax mm
$\bar{x}$	4062	6,5	0,65
s	277	0,5	0,06
ν	6,83	7,20	9,48

Ten Cate Advanced Composites

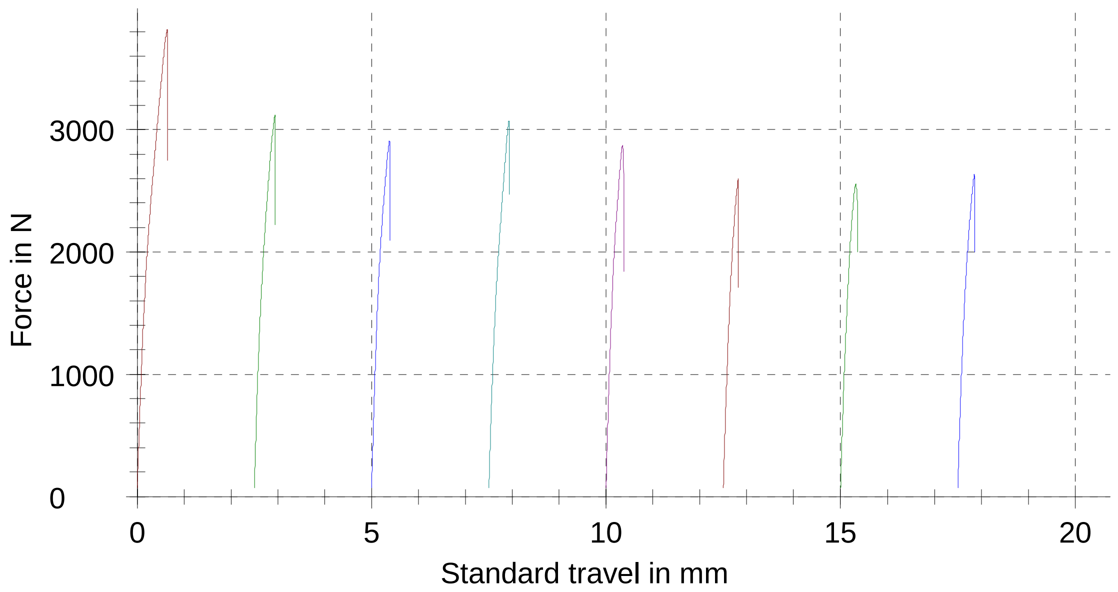
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	18-12-2014
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Loctite 4090	Grips	:	F-0693
Pre-conditioning	:	168 Hrs @ 85°C	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	39	3818	6,1	0,65	NS
	2	40	3117	5,0	0,44	NS
	3	41	2907	4,6	0,39	NS
	4	42	3070	4,9	0,44	NS
	5	43	2873	4,6	0,38	NS
	6	44	2602	4,1	0,32	NS
	7	45	2557	4,0	0,36	NS
	8	46	2637	4,2	0,36	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	2948	4,7	0,42
s	410	0,7	0,10
ν	13,91	14,38	24,59

Ten Cate Advanced Composites

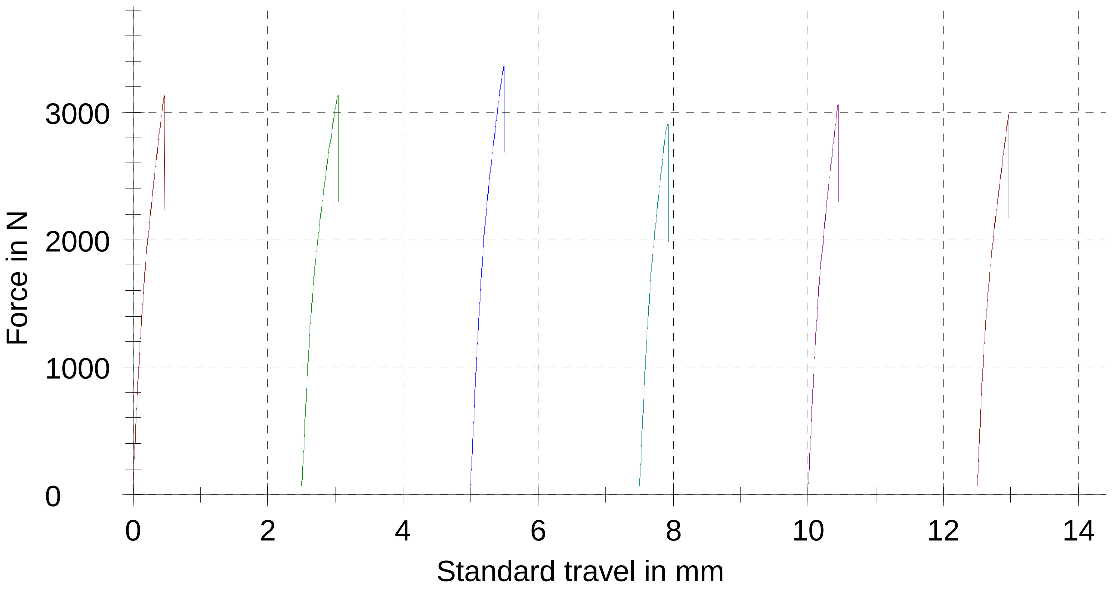
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	18-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Loctite 4090	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	25	3134	5,1	0,47	NS
	2	26	3134	4,8	0,55	NS
	3	27	3361	5,4	0,50	NS
	4	29	2907	4,6	0,43	NS
	5	30	3060	5,0	0,45	NS
	6	31	2986	4,8	0,48	NS



Statistics:

n = 6	Fmax N	τmax MPa	smax mm
$\bar{x}$	3097	4,9	0,48
s	156	0,3	0,04
ν	5,05	5,29	8,94

Zwick, type: Z1474

Ten Cate Advanced Composites

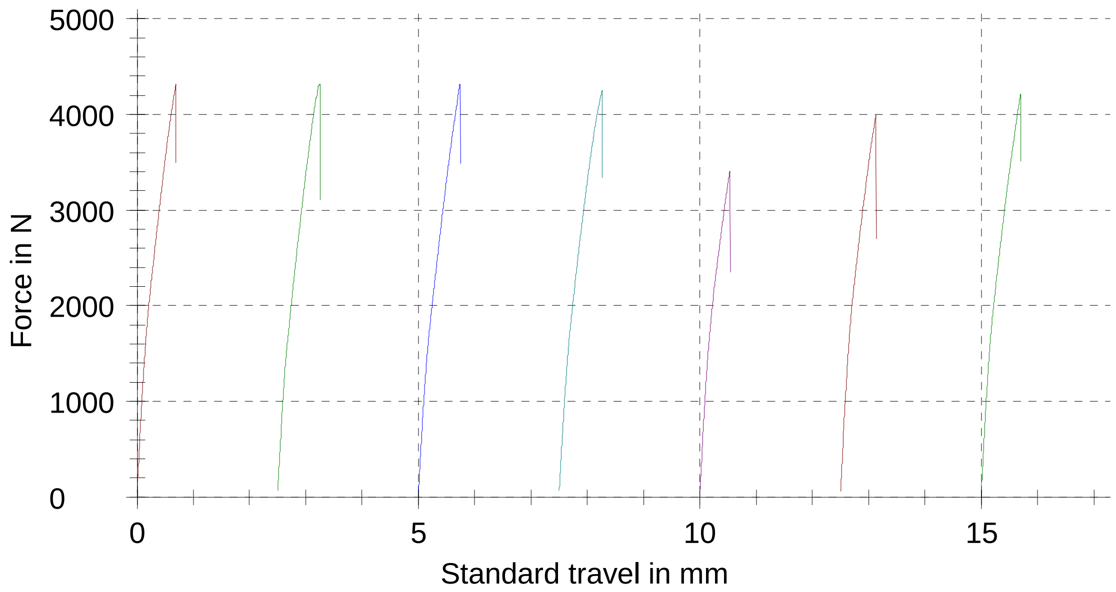
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	19-12-2014
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Loctite 4090	Grips	:	F-0693
Pre-conditioning	:	168 Hrs @ 85°C	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	47	4317	6,9	0,70	NS
	2	48	4316	6,9	0,76	NS
	3	49	4314	7,1	0,75	NS
	4	50	4252	6,9	0,77	NS
	5	51	3409	5,5	0,54	NS
	6	52	3990	6,3	0,63	NS
	7	53	4209	6,7	0,70	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	4115	6,6	0,69
s	332	0,5	0,08
ν	8,07	8,15	11,71

Ten Cate Advanced Composites

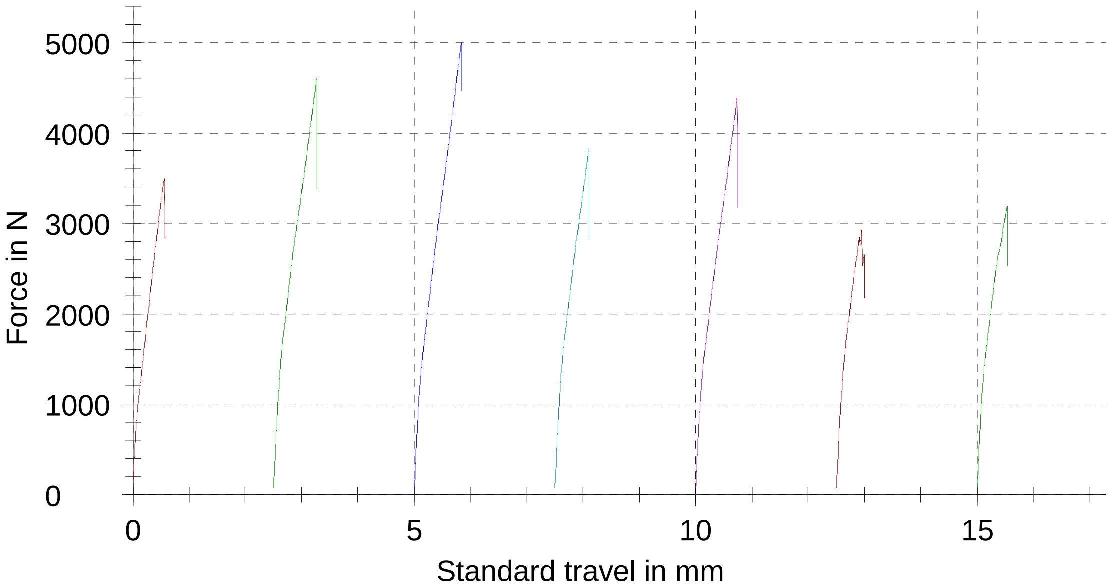
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	09-01-2015
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA (4mm)	Test type	:	Lap Shear
Adhesive	:	Loctite 4090	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	55	3497	5,6	0,57	NS
	2	56	4607	7,4	0,77	NS
	3	57	5004	7,8	0,84	NS
	4	58	3822	6,0	0,61	NS
	5	59	4391	7,0	0,74	NS
	6	60	2925	4,6	0,50	NS
	7	61	3183	5,1	0,54	NS
	✞8	62	3087	5,0	0,45	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	3918	6,2	0,65
s	774	1,2	0,13
ν	19,74	19,74	19,96

Ten Cate Advanced Composites

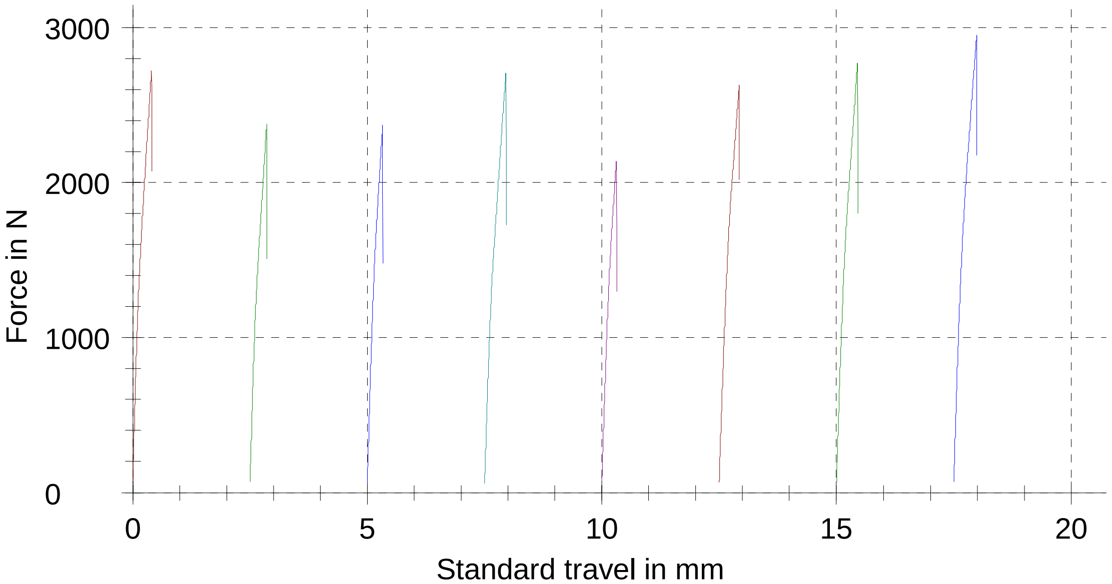
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	09-01-2015
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PA (4mm)	Test type	:	Lap Shear
Adhesive	:	Loctite 4090	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	63	2722	4,4	0,41	NS
	2	64	2377	3,8	0,36	NS
	3	65	2371	3,7	0,34	NS
	4	66	2706	4,3	0,46	NS
	5	67	2140	3,4	0,32	NS
	6	68	2632	4,2	0,43	NS
	7	69	2773	4,5	0,45	NS
	8	70	2953	4,6	0,50	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	2585	4,1	0,41
s	266	0,4	0,06
ν	10,27	10,50	15,87

Ten Cate Advanced Composites

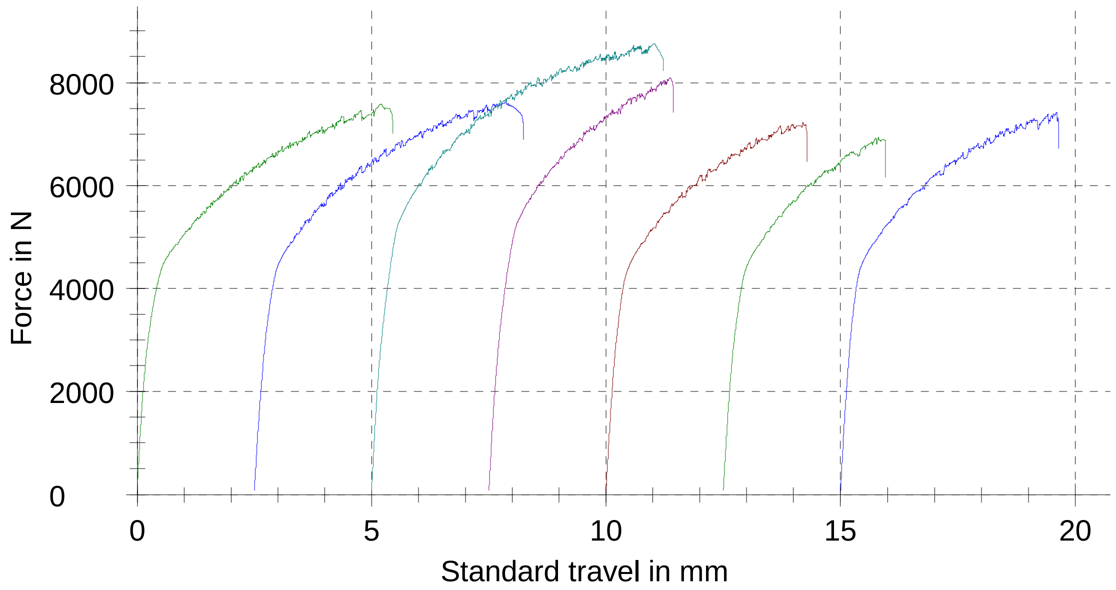
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	09-01-2015
Substrate 1	:	Aluminium	Test standard	:	ASTM-D5868
Substrate 2	:	PP	Test type	:	Lap Shear
Adhesive	:	3M DP-8005	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	✝1	63	7095	5,7	-	NS
	2	64	7577	6,0	5,46	NS
	3	65	7616	6,2	5,75	NS
	4	66	8759	6,8	6,23	NS
	5	67	8090	6,5	3,94	NS
	6	68	7232	5,6	4,28	NS
	7	69	6942	5,5	3,46	NS
	8	70	7426	5,8	4,65	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	7663	6,1	4,82
s	599	0,5	1,01
ν	7,82	7,86	21,04

Ten Cate Advanced Composites

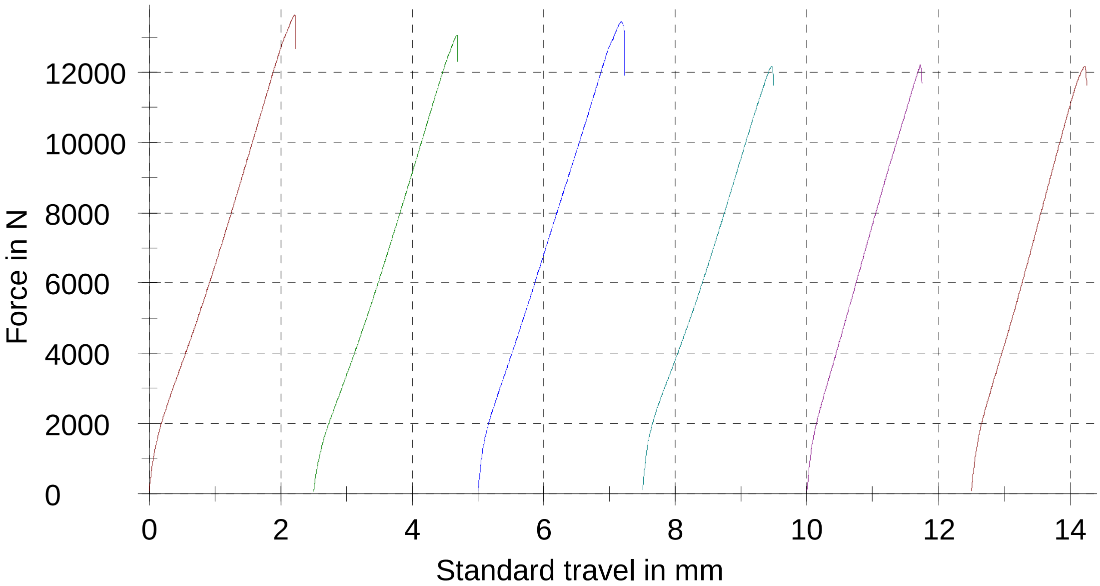
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	09-01-2015
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PP	Test type	:	Lap Shear
Adhesive	:	3M DP-8005	Grips	:	F-0693
Pre-conditioning	:	-	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	55	13632	10,8	2,23	NS
	2	56	13066	10,4	2,19	NS
	3	57	13441	10,7	2,23	NS
	5	58	12179	9,5	1,99	NS
	6	59	12214	10,1	1,75	NS
	7	60	12183	9,8	1,76	NS
	✝8	61	10479	8,5	1,78	NS
	✝4	62	9452	7,4	1,63	NS



Statistics:

n = 6	Fmax N	τmax MPa	smax mm
$\bar{x}$	12786	10,2	2,02
s	676	0,5	0,23
ν	5,28	4,99	11,28

Zwick, type: Z1474

Ten Cate Advanced Composites

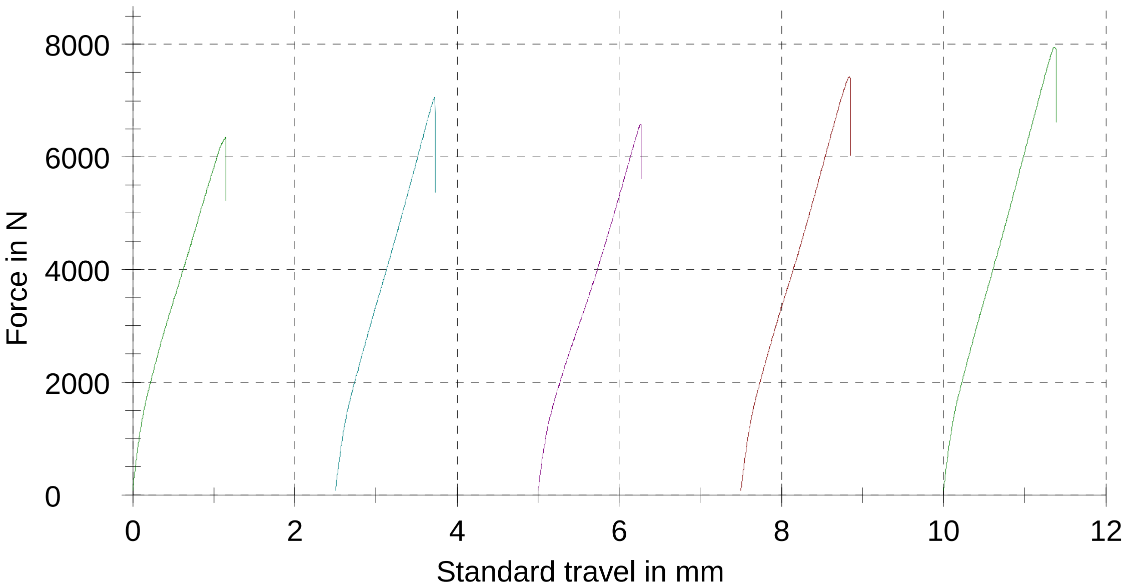
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	12-01-2015
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PP	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15	Grips	:	F-0693
Pre-conditioning	:	0.06 gr. Glass beads 106-212	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	✝1	51	3829	6,2	0,60	NS
	2	52	6348	10,2	1,15	NS
	✝3	53	5603	8,8	1,15	NS
	4	54	7065	11,2	1,23	NS
	5	55	6578	10,5	1,27	NS
	6	56	7420	11,9	1,35	NS
	7	57	7947	12,5	1,39	NS



Statistics:

n = 5	Fmax N	τmax MPa	smax mm
$\bar{x}$	7072	11,2	1,28
s	643	1,0	0,10
ν	9,10	8,49	7,51

Ten Cate Advanced Composites

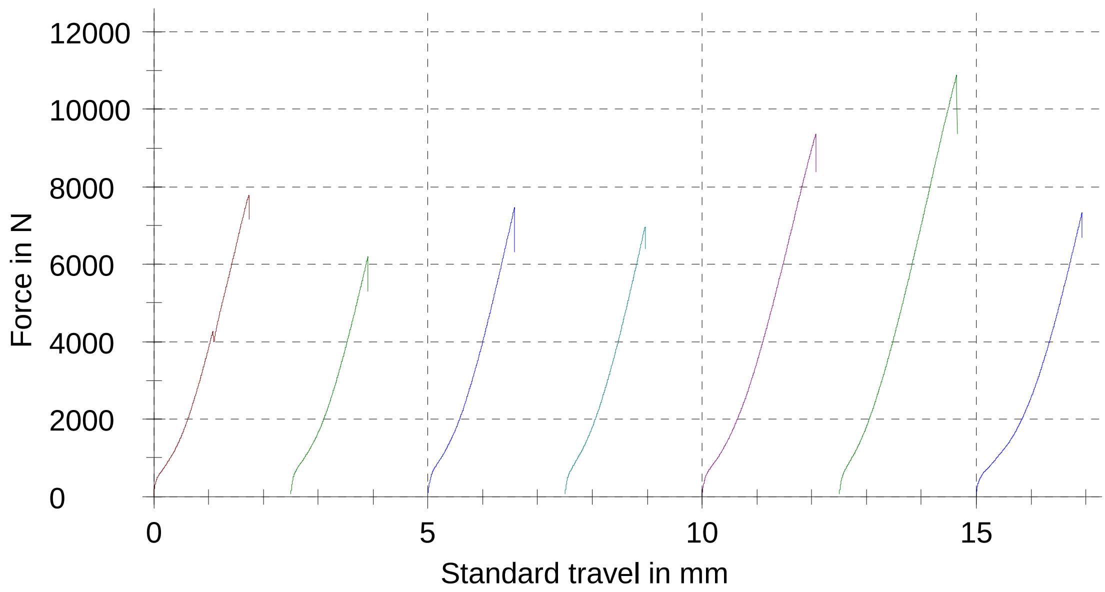
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	16-01-2015
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-AM-15	Grips	:	F-0695
Pre-conditioning	:	0.06 gr. Glass beads 106-212	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	58	7780	12,4	1,74	NS
	2	59	6196	9,8	1,41	NS
	3	60	7472	11,7	1,59	NS
	4	61	6962	11,0	1,46	NS
	5	62	9363	14,7	2,08	NS
	†6	63	5884	9,1	1,85	NS
	7	64	10894	16,8	2,15	NS
	8	65	7336	11,6	1,93	NS



Statistics:

n = 7	Fmax N	τmax MPa	smax mm
$\bar{x}$	8000	12,6	1,77
s	1599	2,4	0,29
ν	19,98	19,08	16,71

Ten Cate Advanced Composites

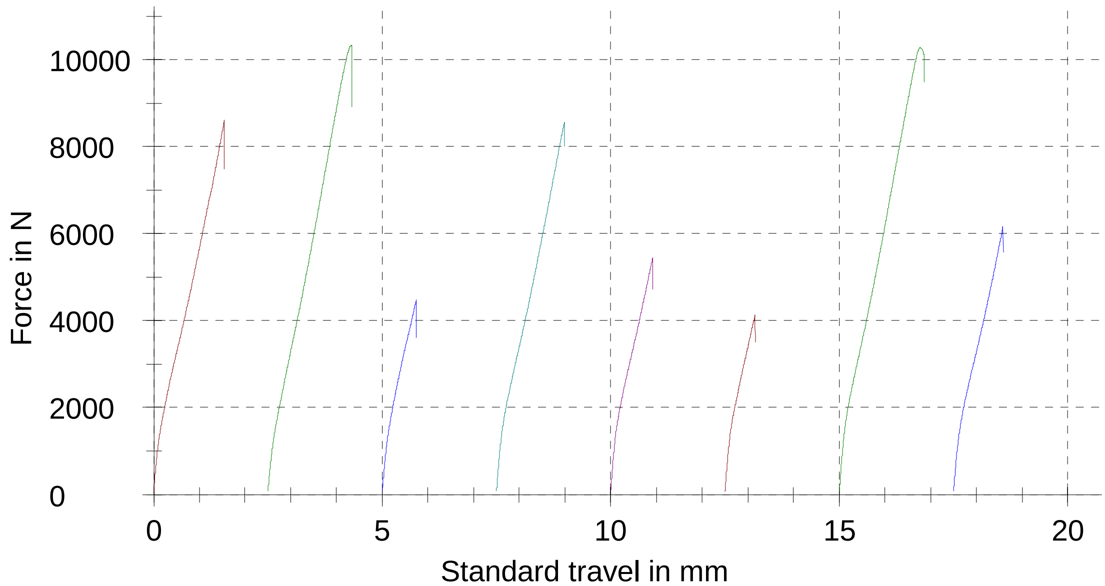
Lap shear properties

Test parameters for testbatch:

Name operator	:	Marco van Oosten	Date	:	23-01-2015
Substrate 1	:	Steel	Test standard	:	ASTM-D5868
Substrate 2	:	PA	Test type	:	Lap Shear
Adhesive	:	Cyanoacrylate 1500 V-MOW-3	Grips	:	F-0693
Pre-conditioning	:	0.06 gr. Glass beads 106-212	Test speed	:	13 mm/min
Test condition	:	23 °C / 50% RH			

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	1	8612	13,5	1,55	NS
	2	2	10340	16,4	1,84	NS
	3	3	4474	7,2	0,75	NS
	4	4	8566	13,7	1,49	NS
	5	5	5458	8,6	0,93	NS
	6	6	4128	6,7	0,67	NS
	7	7	10275	16,5	1,85	NS
	8	8	6154	10,0	1,09	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\overline{x}$	7251	11,6	1,27
s	2511	4,0	0,47
ν	34,64	34,32	37,36

Ten Cate Advanced Composites

Lap shear properties

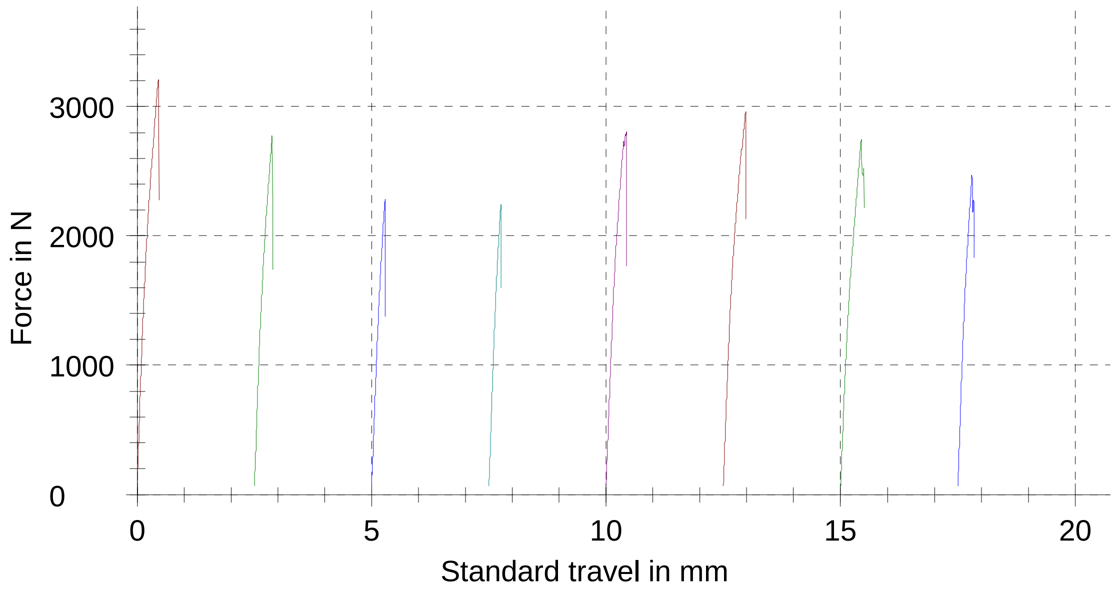
Test parameters for testbatch:

Name operator	:	Marco van Oosten
Substrate 1	:	Aluminium
Substrate 2	:	PA
Adhesive	:	Cyanoacrylate 1500 V-MOW-3
Pre-conditioning	:	0.06 gr. Glass beads 106-212
Test condition	:	23 °C / 50% RH

Date	:	23-01-2015
Test standard	:	ASTM-D5868
Test type	:	Lap Shear
Grips	:	F-0693
Test speed	:	13 mm/min

Testbatch results:

Legends	No.	Specimen code	Fmax N	τmax MPa	smax mm	Failure mode
	1	9	3204	5,1	0,47	NS
	2	10	2775	4,3	0,39	NS
	3	11	2286	3,7	0,30	NS
	4	12	2242	3,5	0,26	NS
	5	13	2803	4,4	0,43	NS
	6	14	2962	4,7	0,48	NS
	7	15	2745	4,4	0,50	NS
	8	16	2470	4,0	0,34	NS



Statistics:

n = 8	Fmax N	τmax MPa	smax mm
$\bar{x}$	2686	4,3	0,40
s	332	0,5	0,09
ν	12,38	12,38	22,77