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AVIV GEDANKEN BRANTA

DEVELOPMENT OF A LASER ASSISTED RECYCLING METHOD FOR CARBON FIBER LAMINATES.

Joinville
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Trabalho apresentado como requisito para obtenção do título de Bacharel em Engenharia Aeroespacial, no Centro Tecnológico de Joinville, da Universidade Federal de Santa Catarina.

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I dedicate this work to my family, as without them, this wouldn’t be possible.

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ABSTRACT

Due to having good mechanical properties, while being lightweight, the usage of carbon fiber reinforced polymers has increased during the last years, and with that the amount of waste generated. Different methods for their recycling already exist, but each have their own disadvantages, such as losing fiber length and loss of the materials mechanical properties. This work aims for the development of a recycling method and a module to test the methods viability, through the removal of material in tape form from a heated detachment area in carbon fiber laminates. The method is to be compatible with machines used in the production of said laminates through laser assisted tape placement processes. For that purpose the module for the process was designed utilizing as many components already present in the machine as possible, but new components also had to be designed and produced. Restrictions for the test laminates were also defined and those were produced. Lastly, the module was tested for the definition of process parameters and to better understand their effects. The method seems promising, but problems and possible improvements in the design were identified and need to be applied before further testing.

Keywords: Carbon fiber. Reinforced polymers. Recycling.

RESUMO

Devido a possuir boas propriedades mecânicas, mantendo um baixo peso, a utilização de polímeros reforçados por fibra de carbono vem aumentando durante os ultimos anos, e com isso o aumento de lixo gerado. Diferentes métodos para a reciclagem deles já existem, no entanto, cada possui as suas desvantagens, tais como a perda de tamanho de fibra, e a redução das propriedades mecânicas do material. Esse trabalho visa o desenvolvimento de um método de reciclagem e um módulo para testar a viabilidade do método, através da remoção de material em forma de fita de uma região aquecida de laminados de fibra de carbono. O método é para ser compativel com máquinas utilizadas na produção destes laminates através de processos de "laser assisted tape placement". Para esse objetivo, o module para o processo foi projetado utilizando a maior quantidade possivel de peças já presentes, mas novos componentes também tiveram que ser projetados e produzidos. Restrições para os laminados teste também foram definidas e estes foram produzidos. Por fim, o modulo foi testado para a definição de parâmetros de processo, e para melhor entender seus efeitos. O método parece promissor, mas problemas e possiveis melhorias foram identificadas, as quais devem ser aplicadas antes de proceder com a testagem.

Palavra-chave: Fibra de carbono. Polímeros reforçados. Reciclagem.

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LIST OF ABBREVIATIONS AND ACRONYMS

ATL	Automated Tape Laying
CF	Carbon Fiber
CFRP	Carbon Fiber Reinforced Polymers
CAGR	Compound annual growth rate
FRP	Fiber Reinforced Polymers
GF	Glass Fiber
GFRP	Glass Fiber Reinforced Polymers
IPT	Fraunhofer Institute for Production Technology
ISO	International Organization for Standardization
LATP	Laser Assisted Tape Placement
PA6	Polyamid 6
Prepreg	Pre-impregnated fiber
TP	Thermoplastics
TS	Thermosets
UD	Unidirectional

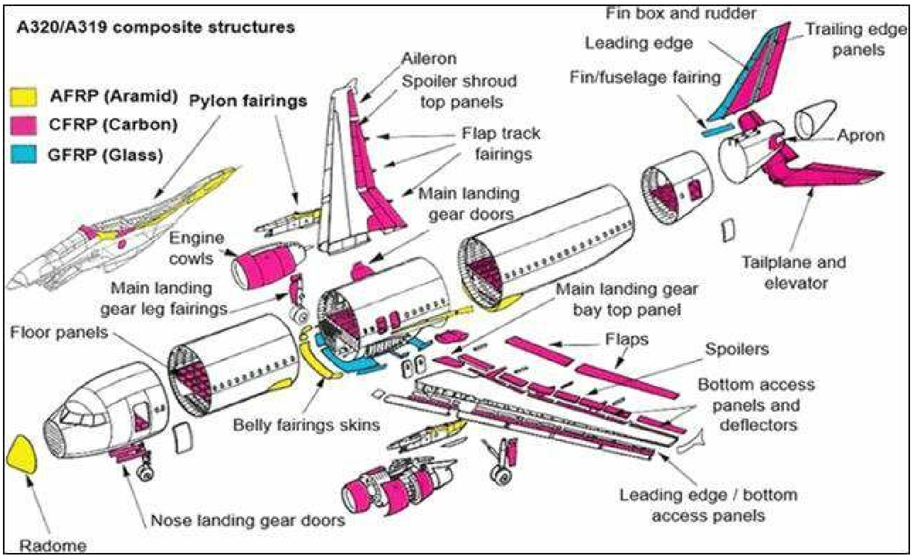
SUMMARY

1 INTRODUCTION

Beginning on the 1960s, high performance composite materials were becoming an important part of the aerospace industry. The development of carbon, boron and quartz fibers enabled the designers to create lightweight structures, while still meeting aircraft flight performance needs (REZENDE; BOTELHO, 2000). Compared to metals, several composite materials have more significant strength characteristics, higher resistance to fatigue, and are more corrosion resistant. Those characteristics enable for lighter aircraft, lower fuel usage per passenger, and a decrease in maintenance costs (HARIZ et al., 2021).

Fiber Reinforced Polymers (FRP) are the most commonly used type of composite materials in aerospace engineering. Carbon fiber Reinforced Polymers (CFRP) in specific are of great interest to the industry, due to their high potential for reducing weight. In 2009 Boeing released the Boeing 787, and in 2013 Airbus released the A350, which have a material composition respectively of 50% and 52% CFRP (VAN GROOTEL et al., 2020). Other types of FRP used in the industry are Glass Fiber Reinforced Polymers (GFPRs) and aramid fibers, the presence of these types of composite materials can be seen on figure 1, and which components are made from them, which showcases their widespread use in the industry. (MOURITZ, 2012).

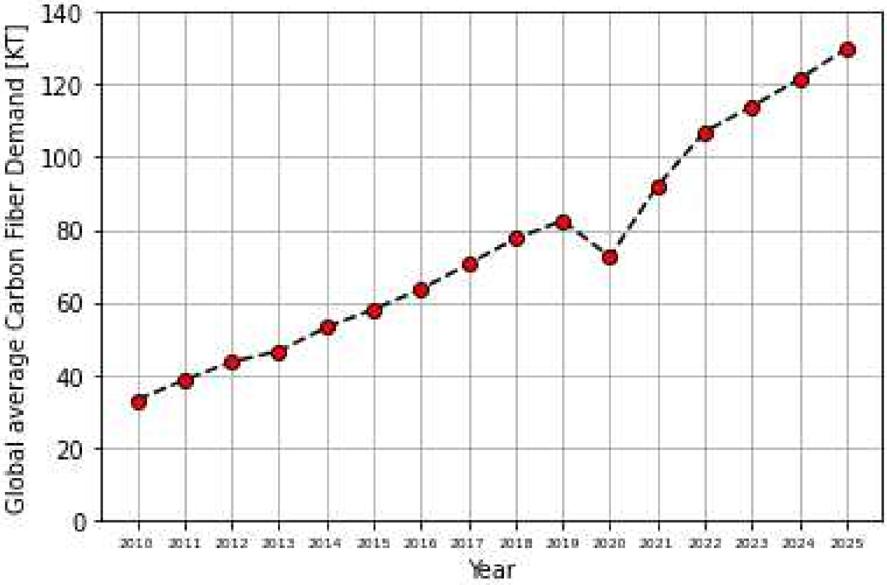
Figure 1 – Components made of FRP in Airbus A320/A319.



Source: Mouritz (2012).

This increase in the production and usage of FRP materials worldwide is showcased in figure 2 , which shows the global demand for Carbon fiber between 2010 and 2025 (SAUER; SCHÜPPEL, 2022). The aforementioned increase can also be seen in the aerospace industry, with a Compound Annual Growth Rate (CAGR) between 2010 and 2019 of 7%, a CAGR between 2019 and 2022 of -10% (which can be attributed to the COVID pandemic), and a projected CAGR between 2022 and 2027 of 6% (JEC, 2023). Said increase in FRP usage generates an increase in waste made of this material, and for that reason, new recycling methods also have to be developed for it.

Figure 2 – Global demand of Carbon Fiber.



Source: Sauer e Schüppel (2022).

Current recycling methods, maintaining part of the fiber length, have an energy demand of 20 MJ up to 90 MJ per kg of recycled carbon fiber (FAZIO et al., 2023), that can be compared to the energy demand of 198-595 MJ/kg used for the production of virgin fibers (MENG et al., 2018). Virgin carbon fiber has a current cost to manufacture of US$33-$66/kg (CARBERRY, 2008) but the recycling of these fibers can be achieved at a cost of under US$5/kg (MENG et al., 2018). In conclusion, these signify a a reduction in energy consumption between 54.5% and 96.7%, and a cost reduction between 84.8% and 92.4%, making the recycling of these materials financially and energetically viable.

The usual usage of FRP is in the form of laminates composed of several layers (ROSATO; ROSATO, 2005), and different recycling processes for these already exist. They can be classified in three different groups: Chemical, Thermal and mechanical recycling. However, all of these methods have their limitations and disadvantages, as can be seen on Fazio et al. (2023), such as high energy consumption and loss of fiber length. With this in mind, the development of a laser assisted peeling of FRP laminates built with the layering of pre-impregnated fibers (prepregs), as a recycling method is proposed, which would alleviate some of the problems encountered with current recycling methods.

Therefore, the objective of this thesis is to understand the currently used recycling processes, then develop a recycling method and design a module for the validation of said method, to be attached to the Prepro2D with basis on the patent "METHOD AND DEVICE FOR RECYCLING THERMOPLASTIC FIBRE-REINFORCED COMPOSITE MATERIAL" by Janssen (2019). The Prepro2D, which can be seen in figure 3, is a machine currently used at Fraunhofer Institute for Production Technology (IPT), for the manufacturing of FRP laminates with the Laser Assisted Tape Placement (LATP) of UniDirectional (UD) prepreg tapes.

Figure 3 – PrePro2D.

Source: Fraunhofer Institute for Production Technology (2024).

1.1 OBJECTIVES

1.1.1 General Objectives

The main objective of this work is the development of an recycling method for FRP laminates compatible with the LATP machine PrePro2D and of a module to test the methods viability.

1.1.2 Specific Objectives

- Develop a recycling method compatible with the PrePro2D.
- Design a module to test the methods viability.
- Assess the necessary requirements for a recycling friendly component.
- Understand the effect of the process parameters in the recycling process.

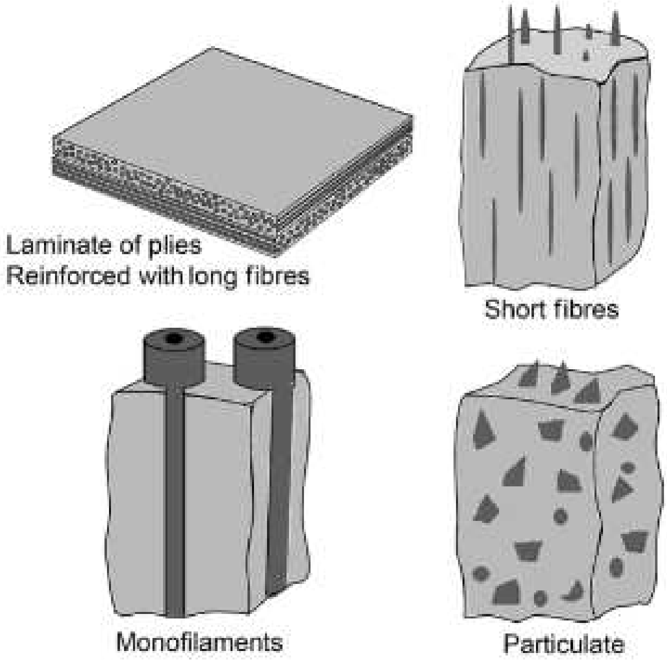
2 STATE OF THE ART

Before the development of the process, first it is needed to understand some of the different aspects correlated with it. For this reason it is looked into the materials which make the laminates, the production method of these laminates and some of the existing recycling methods as well.

2.1 COMPOSITES

Composite materials are made through the synthetic assembly of two or more components, a filler or reinforcing agent and a matrix binder. Composites are categorized with basis on their structural form, examples can be seen on figure 4, they are: Fibrous, composed of fibers in a matrix; Laminar, composed of layers of materials; Particulate, composed of particles in a matrix (ROSATO, 1982).

Figure 4 – Different examples of composites configuration.



Source: Hull e Clyne (1996).

The matrix material can be polymeric, metallic or ceramic, although for industrial use the most common are polymers, more specifically thermosets and thermoplastics. The reinforcements can also be polymeric, metallic or ceramic, they can be in the form of long and short fibers and particulates, but in industrial settings they are usually long fibers of either carbon or glass (HULL; CLYNE, 1996).

Composites allow for the designer, by choosing the matrix and reinforcement material, the possibility to tailor their final composite to meet different project demands. The goal with their creation is to fulfill certain desired properties, such as a higher strength to density ratio from the reinforcements while keeping the matrix resistance to heat and flames, for example. The properties of said composites are usually superior to that of other materials. (ROSATO, 1982)

2.2 FIBER REINFORCED POLYMERS (FRP)

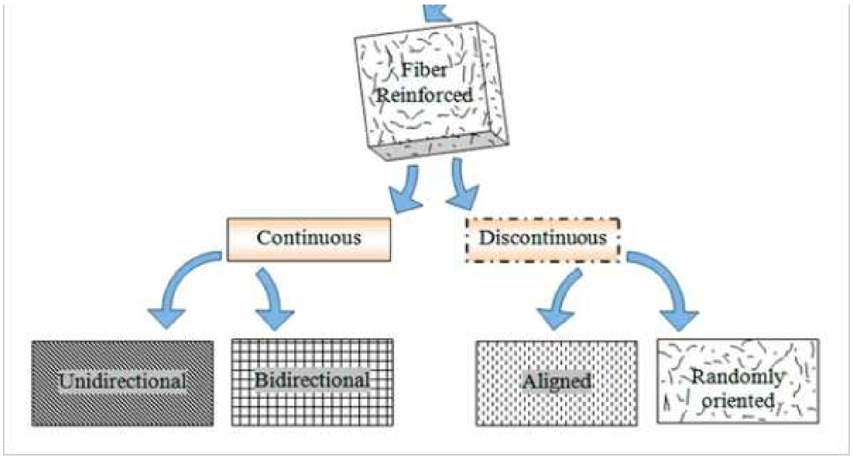
Fiber Reinforced Polymers (FRP), also known as Fiber Reinforced Plastics are a subclass of composite materials, they are composed of a polymer matrix reinforced with fibers. The fibers can either be synthetic, such as Glass Fiber (GF) and Carbon Fiber (CF), or natural, such as flax and jute. The most commercially available FRPs are either CF or GF in thermoset matrices, but thermoplastics are also used because of their better moldability after their initial production (MASUELLI, 2013).

In FRP materials, the matrices works as a binder, it has a function of keeping the fibers together and in place, it gives shapes to the components, it is where the loads are applied and then those are transfered to the fibers. The purpose of the fibers is to reinforce the weaker matrix material, because of its higher tensile strength and stiffness (ROSATO; ROSATO, 2005).

FRPs can offer high strength to weight ratio, durability, stiffness, damping property, flexural strength, and resistance to corrosion wear, impact, and fire, and for these reasons their use is growing in a lot of different industries, such as aerospace, construction and automobile industries (RAJAK et al., 2019).

Composites can be classified on fiber length and orientation. Those with long fibers are classified as continuous fiber reinforced composites, and those with short fibers are classified as discontinuous fiber reinforced composites, these classifications can be seen on figure 5. A longer fiber length allows for a greater load transfer, it also restrains the growth of cracks. The arrangement of the fibers defines the properties of the composite and should be chosen depending on the use of the material (RAJAK et al., 2019).

Figure 5 – Classification of FRP.

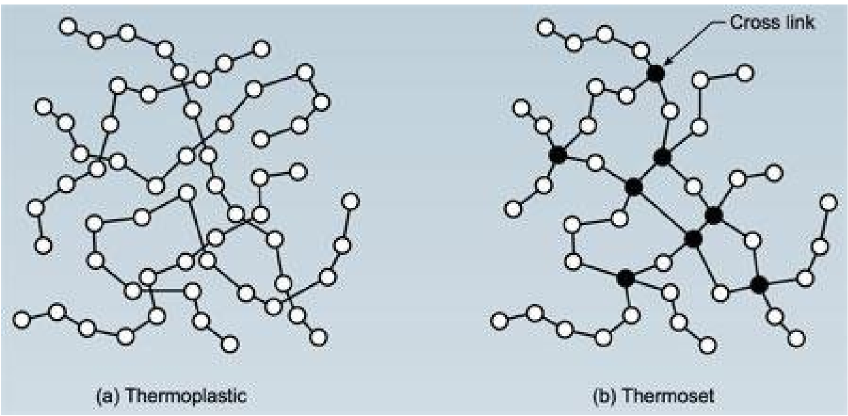


Source: Modified from Rajak et al. (2019).

2.2.1 Matrix Materials

The binding matrix materials are made of polymers, and these can be separated in 3 different categories, Thermoplastics (TP), Thermosets (TS) and Elastomers, but only TP and TS are used in FRP, the molecular configuration of these two, can be seen on figure 6 (ROSATO; ROSATO, 2005).

Figure 6 – Thermoplastics and Thermosets molecular configuration.



Source: Bobo (2013).

Thermosets are plastics that, when high enough temperatures are reached will solidify, and crosslinks will be created between their different molecules, as can be seen on figure 6, for that reason after their curing process is done, if they are reheated, they will not soften again. On the opposite side, in the molecular configuration of TP, the chains are made of repeating molecules that do not interconnect when heated, and for that reason they will harden once cold, but by applying heat on them they will once again soften, and this cycle can be repeated indefinitely (ROSATO; ROSATO, 2005).

2.2.2 Fiber Materials

The fiber materials, which in this case are the reinforcing agent, can be classified in natural and synthetic fibers, these categories with examples can be seen on figure 7. Natural fibers are those found in nature, they are extensively available and easy to obtain, while synthetic fibers are human-made produced by chemical synthesis (RAJAK et al., 2019).

Figure 7 – Categorization of fiber types.

Source: Rajak et al. (2019).

Natural fibers contain some important characteristics, such as biodegradability, low cost and reduced weight, however when compared to synthetic fibers, they possess a lower tensile strength, and lower thermal stability (RAJAK et al., 2019). For these reasons, synthetic fibers are the most commonly used reinforcements in the industry, more specifically GF and CF (ROSATO; ROSATO, 2005).

GF are the most used overall, because of their lower cost when compared to CF, while while exhibiting good properties, such as high temperature resistance and high tensile strength. On the other hand, CF represents specialty applications, where high performance is necessary, they exhibit higher tensile strength compared to GF but at a more expensive cost and for that reason, their use is more selected (ROSATO; ROSATO, 2005).

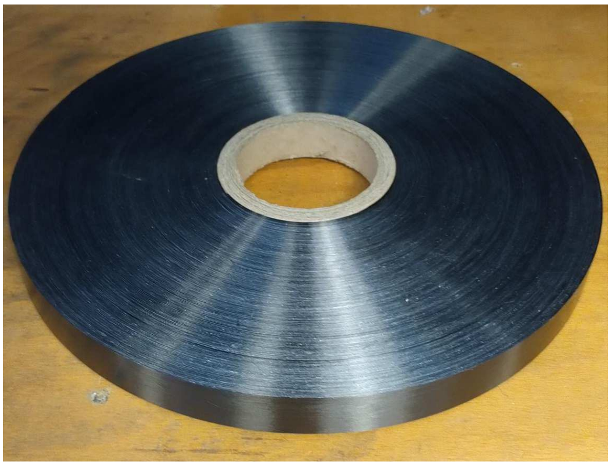
2.3 PRE-IMPREGNATED FIBERS (PREPREG)

Prepregs are fiber sheets impregnated with polymer resins that have not yet been cured, for this reason they are still flexible and easier to handle, removing the necessary step of wetting the fibers before curing it (MCKEEN, 2020).

Prepregs are made from a range of materials, both for the fibers and for the resin. They are also available in a lot of different formats, such as UD tapes, two-dimensional and three-dimensional fabrics (MARSH, 2002). TP prepregs present advantages when compared to TS prepegs, because of their ability to reshape with heat, they can be stored dry and indefinitely at room temperature, also, the tapes are able to be rolled into spools (AKONDA et al., 2016).

For the production of FRP components through LATP, prepreg TP tapes with varying sizes are used (GROUVE, 2012). An example of these tapes can be seen on figure 8, which is a spool of Unidirectional CF, which means all the fibers are parallel and in the direction of the tape, pre-impregnated with the thermoplastic Polyamide 6 (PA6). This tape is used at the IPT, for different LATP processes including those for the production of FRP Laminates.

Figure 8 – UD PA6-CF prepreg tape.



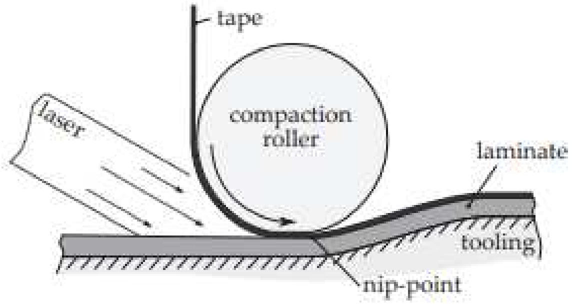
Source: Author.

2.4 LASER ASSISTED TAPE PLACEMENT (LATP)

Automated Tape Laying (ATL), are processes comprised of the automated deposition of prepreg tapes in a tooling to gradually shape the component (GROUVE, 2012). The utilization of thermoplastic prepregs in ATL is a highly efficient method of production for CFRP components, specially in Aerospace engineering. For in-situ consolidation the heating can be provided from hot gas and different types of lasers. When the heat source are focalized lasers, this process becomes known as Laser Assisted Tape Placement (LATP) (SREBRENKOSKA et al., 2020).

A schematic for the LATP process can be seen in figure 9 . It is composed of the automated deposition of prepreg TP tapes on pre-defined paths by a robotic arm. The freshly laid tape is bonded to the underneath layers through the application of pressure and heat. The heat is supplied by the laser and the pressure can be supplied by a compaction roller or shoe (GROUVE, 2012).

Figure 9 – Schematic of LATP process.



Source: Grouve (2012)

Several advantages can be seen by using this method for the production of CFRP laminates, such as:

- The placement system allows for different orientation of the fibers, which can be tailored depending of the component load (KERMER-MEYER, 2015).
- The in-situ consolidation of the prepreg tapes removes the need for an autoclave cycle, making the process cheaper, less time consuming, and reducing its energy consumption (SREBRENKOSKA et al., 2020).
- When compared to other heating sources, such as hot gas, the utilization of lasers provide higher energy density and a more focalized heating. That enables for precise high velocity placements (GROUVE, 2012).

Different formats of components can be obtained through this process. They depend on the tooling format, the tape placement programming of the robot, the tape size and many other parameters. A similar process also exists called Laser assisted tape winding, in which the tape deposition is made around a rotating axis (KERMER-MEYER, 2015). Those different shapes produced by LATP processes can be seen on figure 10.

Figure 10 – CFRP components made with LATP.

Source: Brecher et al. (2014)

Several parameters affect LATP processes, such as:

- Laser power and process speed affect the temperature of the material, important for melting of the matrix (GROUVE, 2012).
- The pressure applied between the tape and the substrate, important for the development of good contact between them (GROUVE, 2012).
- Laser angle dictates how much of the laser power goes towards the tape, and how much goes towards the substrate (KERMER-MEYER, 2015).

An important region in the process is called the nip point, it is where the tape and the substrate first meet and layer contact is made. Beginning on this point autohesion between the tape and substrate starts.

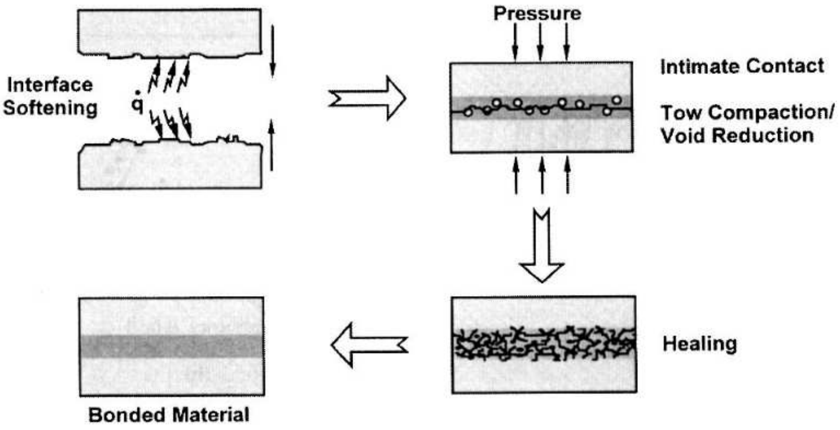
2.4.1 Interlaminar bonding of thermoplastics

An important aspect in LATP processes is the interlaminar bonding of thermoplastics, necessary for the production of different components.

The bonding process can be seen on figure 11 , it consists of two different phenomena happening simultaneously: First, the development of intimate contact between the layers, with the removal or minimisation of void spaces; Second, the interdiffusion of polymers chains across the intimate contact region, also known as healing (YANG;

PITCHUMANI, 2002b). The result of this process is measured by the mechanical properties in the bond region, and the closer they are to the rest of the material the better, giving visually inseparable plies(MODI et al., 2013).

Figure 11 – Schematic of thermoplastic bonding process.

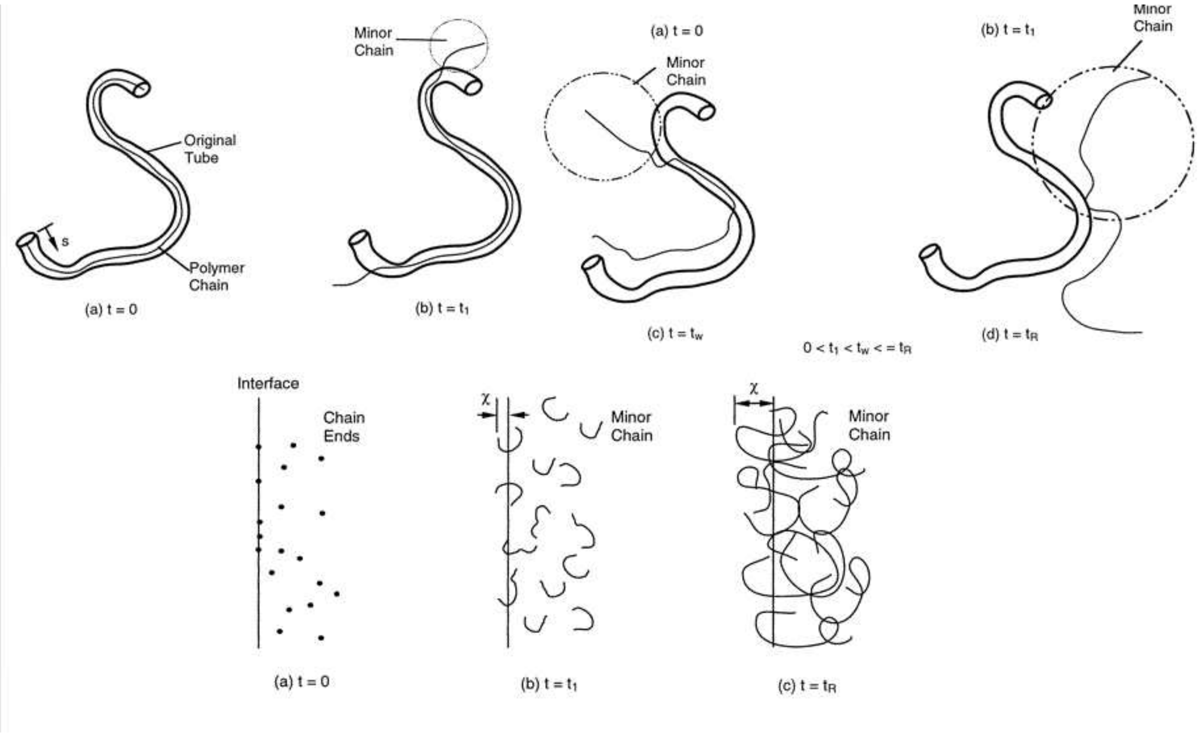


Source: Yang e Pitchumani (2002b)

The development of intimate contact is made by the application of heat and pressure on the interface between the thermoplastic surfaces. The heat softens the material and the pressure spreads the asperities, removing the void spaces in the interface resulting in a contact area known as intimate contact. This development is a function of multiple manufacturing and material parameters, such as: pressure, temperature, time and the geometry of the surface asperities (YANG; PITCHUMANI, 2002b).

In the regions where intimate contact has been achieved, because of thermal motion, polymeric chains with diffuse across the interface, and entangle with chains on the other side, as this diffusion increases the interface vanishes and cannot be differentiated from the rest of the material anymore (GROUVE, 2012). This process can be described by the reptation theory of chain mobility developed by DE Gennes (1971) and seen on figure 12, in the model, a polymeric chain is encased by a tube representing the entangled neighboring chains surrounding it. The chain can only move along the curvilinear length of the tube and after a period, due to its Brownian motion, it will leave the tube creating “minor chains”. With time, these minor chains will grow and some will cross the interface, contributing to the development of bond strength in the interface (YANG; PITCHUMANI, 2002a).

Figure 12 – Minor chain development and diffusion.

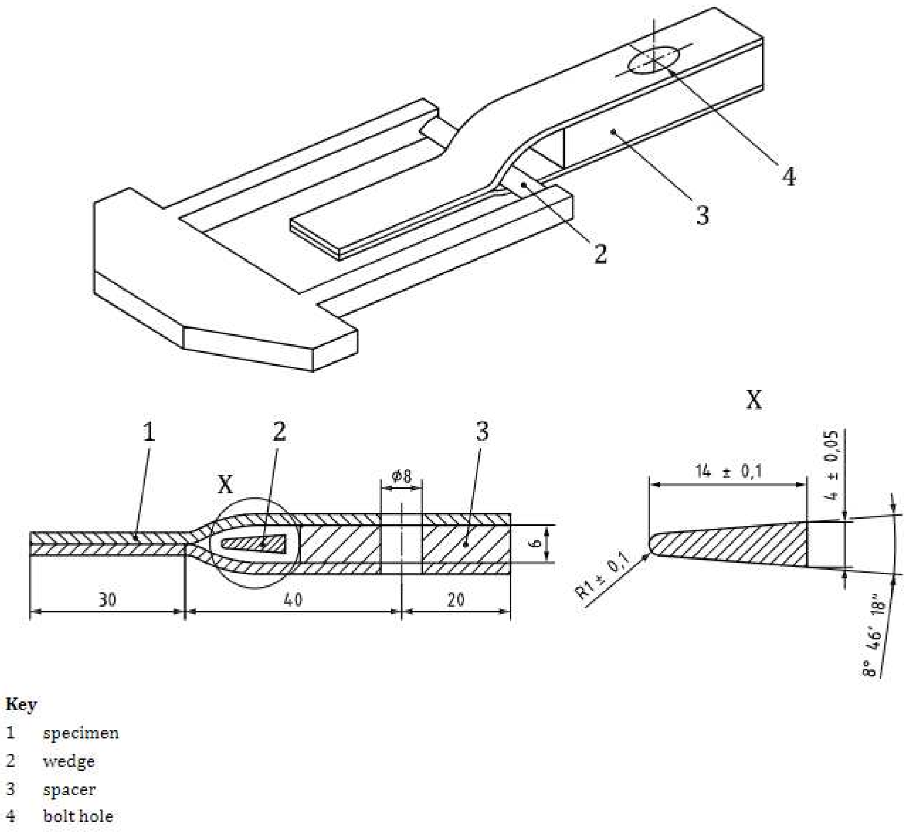


Source: Modified from Yang e Pitchumani (2002a)

2.4.1.1 Wedge peel test

The wedge peel test is designed to evaluate the bonding between two adherents. It evaluates the specimen's resistance to cleavage either as a force or energy. The cleavage of the bonding region is caused by the impact of a wedge moving at a high speed (ISO, 2019). The setup as described by the standard ISO 11343 can be seen on figure 13.

Figure 13 – Wedge peel test setup.



Source: ISO (2019)

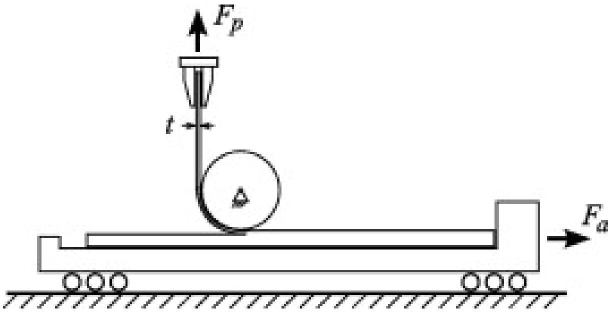
The wedge is aligned and pulled through the adhesive joint, in a typical test the impact velocity is of 2 m/s. With this test a graph of either force-time or force-displacement can be created, and information such as cracking force and the failure point can be found. (ISO, 2019)

As shown in Satheesh et al. (2018), the wedge peel test can also be used to characterize the interlaminar bonding of different plies in thermoplastics, identifying the necessary force for breaking the bond.

2.4.1.2 Mandrel peel test

The mandrel peel test is used predominantly for the determination of adhesive fracture toughness of metal-polymer laminates. The setup for this test as shown in figure 14, consists of the to be tested laminate attached to a table mounted on linear bearings as to reduce friction. The peel arm is bent around a roller, and a tensile force applied to it. An alignment force is also applied to the sliding table (KAWASHITA et al., 2006).

Figure 14 – Mandrel peel test setup.



Source: Grouve et al. (2013)

The procedure consists of two separate tests, first of an unbonded specimen, with the objective of determining the friction coefficient and plastic bending energy of the peel arm. Second, of the bonded specimen, and with these two results, the adhesive fracture toughness for the second test can be isolated and obtained (KAWASHITA et al., 2006).

The mandrel peel test, is shown by Grouve et al. (2010) to also be valid in the evaluation of the weld strength of prepreg thermoplastic tapes. The amount of plastic work done by the tape was found to be negligible. In this case the peel arm is a piece of the tape itself, and a peeling speed of 15 mm/min was used.

2.5 RECYCLING OF FRP LAMINATES

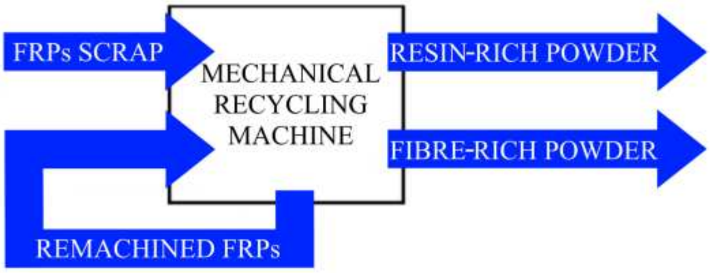
Different methods already exist for the recycling of FRP components, and they can be divided into three main categories, they are: Chemical, which consists of matrix depolymerisation with fibre liberation; Thermal, the deterioration of the matrix using high temperatures, releasing the fiber content; Mechanical, the mechanical fragmentation of the material into smaller pieces, or powder (FAZIO et al., 2023).

The recycled material will have different characteristics depending on the method used, such as fiber length, mechanical properties and surface quality (FAZIO et al., 2023). These methods, and their resulting characteristics will be discussed on the subsections bellow, pinpointing the positives and negatives of each.

2.5.1 Mechanical Recycling

Mechanical recycling of FRP consist in the breakdown of the material in smaller pieces, the subsequent grinding of those into finer dusts or powders and finally the separation of fiber-rich particles and resin-rich particles (GHARDE; KANDASUBRAMANIAN, 2019), a general schematic of the process can be seen on figure 15. These ground materials have two purposes, either to be used as fillers or reinforcements in other composites, however their use as filler is not economically viable due to the cheapness of other commonly used fillers (OLIVEUX et al., 2015).

Figure 15 – General schematic of FRP mechanical recycling.



Source: Fazio et al. (2023)

The mechanical recycling is characterized by its simplicity and low cost, but the resulting fiber length is very short, limiting its use. The properties of the recycled material depends on how well the separation process is done, the size of the powder particles, and the process used in the breakdown of the components (CHEN et al., 2023).

In regards to the environment this process possesses a very low energy demand, between 0.1 MJ and 4.8 MJ per kg of recycled material, being a very energy efficient method for recycling (FAZIO et al., 2023). But, at the same time, it generates a lot of resin and fiber dust, which present a health risk for the process operators, and pollutes the environment (CHEN et al., 2023).

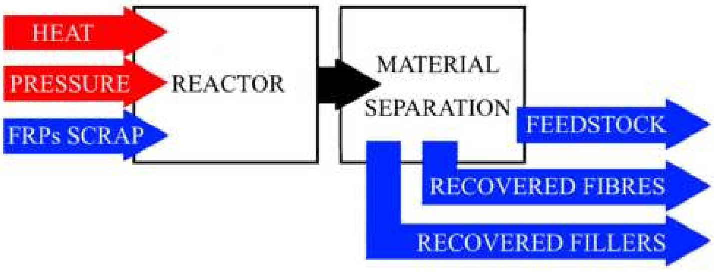
Different equipment can be used to run this process. First the primary component is broken down into smaller pieces by shredding mills, crushing mills or slow speed cutting. After that, they are granulated into finer particles by a high-speed mill or rotary cutter. Finally they are separated into fibrous particles and resin particles by either a cyclone, a sieve or an electrostatic separator (GHARDE; KANDASUBRAMANIAN, 2019).

The benefits of this type of recycling, is the low energy usage. While the downsides are the generation of fiber dust, which pose a health risk to the operators, and the loss of continuous fibers, resulting in a significant reduction in the material's mechanical properties.

2.5.2 Chemical Recycling

The chemical recycling process consists of dissolving the matrix material in a chemical solution into its basic monomers, oils and gasses, a general schematic of this process can be seen on figure 16 . These processes are subdivided in three categories depending on the solvent used, they are called hydrolysis if a water-based solution is used, glycolysis if methanol, ethanol or acetone are used and acid digestion in the case of acid usage (FAZIO et al., 2023).

Figure 16 – General schematic of FRP chemical recycling.



Source: Fazio et al. (2023)

For this process to work, the usage of appropriate and specific equipment is necessary, due to the severe processing conditions employed. The process has an energy demand of 20 MJ/kg up to 90 MJ/kg for the material recycled, due to its usage of high pressure and temperature for an extended period of time (FAZIO et al., 2023).

Some more specific methods can be described, such as the Super/Subcritical Fluid Method which consists of resin degradation in water or alcohols solution under high pressure and temperature. The removal rate of the resin material is highly dependant on the temperature and pressure, with values as high as 400°C and 27 MPa being necessary, and even then, full removal of the matrix material is not achieved (CHEN et al., 2023).

Another method currently used is the electrochemical recycling, which consists of the usage of high electrical currents for matrix degradation and removal. The component is placed in a water solution, and electrical pulses are generated between electrodes and transferred to the material. This method utilizes a high amount of energy, making it impractical for use on GFRPs because this energy consumption is sometimes higher than the one to produce virgin fibers (FAZIO et al., 2023).

Lastly, acid digestion is a process in which different acids and catalysts solutions are used for matrix depolymerisation. This method can be done at atmospheric pressure and low temperatures, but its main drawback is the usage of expensive apparatus (FAZIO et al., 2023).

The main benefit of these methods is the retaining of the fiber length. While the disadvantages are their high energy consumption, and the loss of the matrix material, being necessary for the fibers to be reimpregnated (CHEN et al., 2023).

2.5.3 Thermal Recycling

Thermal recycling consists of the decomposition of the matrix in FRP materials through high temperatures, thus releasing the fibers. It is currently the only commercially used recycling method for CFRP, due to its ease in large scale applications (CHEN et al., 2023). These methods can be separated in different techniques, such as fluidised beds and pyrolysis (GHARDE; KANDASUBRAMANIAN, 2019).

The fluidised bed technique consists of placing smaller pieces of FRP materials into a silica sand bed, which is fluidised with a stream of air or nitrogen, ranging from 450°C to 550°C, dissolving the matrix material. The fibers are then removed from the gas stream, and pass into a combustion chamber, where the polymer is oxidised and its energy recovered (GHARDE; KANDASUBRAMANIAN, 2019). The downside of this method, is that it is responsible for a reduction in the mechanical properties of the fibers, sometimes causing a 50% reduction in its values (FAZIO et al., 2023).

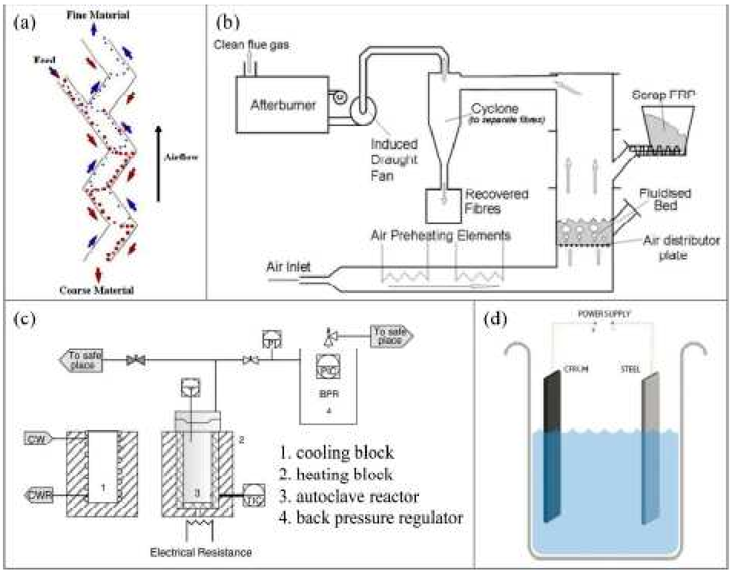
Pyrolysis consists of the decomposition of the matrix into solids, oils, gases and char substances through an inert atmosphere, in which the material is heated up to 1000°C, thus releasing the fibers. This method has an energy consumption estimated up to 30 MJ per kg of material, but part of this energy can be recovered by using some of the products of the process as fuel (FAZIO et al., 2023). This method causes significant oxidation in the fibers, resulting in heavy mechanical properties loss in the recycled fiber, up to 30% loss of strength, in the case of CF (CHEN et al., 2023).

The main benefits of thermal recycling is its ease of scalability and the retaining of fiber length. While on the downside, it causes a significant reduction in the properties of the materials (CHEN et al., 2023).

2.5.4 Recycling conclusion

Some of the previously described methods for FRP recycling can be seen on figure 17. In (a) we have a mechanism to separate fibrous and resin particles for mechanical recycling. In (b) we have a schematic for a fluidised bed device, a method of thermal recycling. In (c) a Supercritical fluid recycling device, and (d) a electrochemical recycling schematic, both are types of chemical recycling (CHEN et al., 2023).

Figure 17 – (a) Air classifier for mechanical recovery; (b) Fluidized bed device; (c) Supercritical recycling device; (d) Electrochemical recycling device



Source: Chen et al. (2023)

As shown in Fazio et al. (2023), also exemplified in the past subsections, all the different techniques and methods for recycling of FRP components have their benefits, while presenting major drawbacks, these are summarized on table 1.

Table 1 – Summary of the recycling methods.

Method category	Advantages	Disadvantages
Mechanical recycling.	Low energy consumption.	Generation of fiber and resin dust. Loss of continuous fibers.
Chemical recycling	Retaining of fiber length.	High energy consumption. Need of fiber reimpregnation.
Thermal Recycling.	Ease of scalability. Retaining of fiber length.	Significant reduction of the mechanical properties.

Source: Author.

New recycling methods for FRPs are being developed, such as the envisioned by the patent number "PCT/EP2017/073670" by Janssen (2019). In which the fiber composite material is pulled of the remaining component, in tape form, with heat in the detachment area, and collected in a storage roll. The process is also characterized in the usage of a separating tool, to separate the pull-off layer from the component.

3 DEVELOPMENT

For a successful and efficient design process a methodological approach to problem-solving needs to be taken (PENNY, 1970). A set of decision-making processes and activities, evolved by years of usage and proven to work can remove unnecessary steps and create a framework for the development process of the component (LEAKE; BORGERSON, 2022).

Based on Penny (1970) and Leake e Borgerson (2022) the guidelines for design process can be defined. The first step is the problem definition, which is the problem to be solved, and in this case has been already defined. Then, the design goals need to be chosen, which are desired characteristics of our solution. Lastly, the design constraints are set, which are limiting boundaries of the design (LEAKE; BORGERSON, 2022). These criteria in relation to this design can be seen on table 2.

Table 2 – Design criteria.

Problem definition	Development of a recycling method for FRP laminates
Design goals	Preserving the fiber length of the tape. Usage of components already present on the PrePro2D. Quality of the removed tape.
Design constraints	Compatible with the Prepro2D.

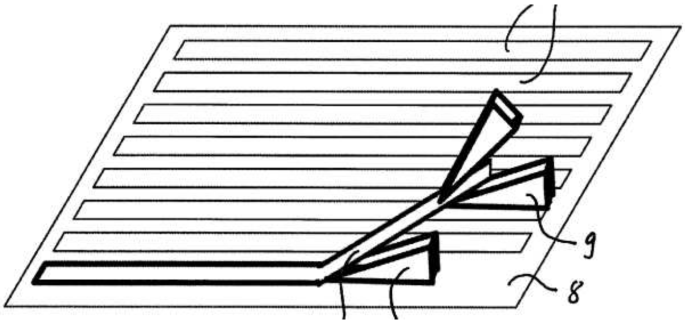
Source: Author.

No performance design goals were set, because the purpose of the module is to test the recycling method for FRP laminates through the peeling of individual tapes. At the moment, the focus is not on obtaining a speedy process, but a working one.

With basis on the patent by Janssen (2019), which describes a general idea for the recycling of FRP components, through the pull-off of material in tape form, from a heated detachment area, assisted by a separating component and then stored in a storage element, shown in figure 18. Alongside the design criteria, the system's subfunctions, which are necessary for a robust design (LEAKE; BORGERSON, 2022), can be defined and are shown bellow.

1. Generate a peeling force;
2. Separate tape from component;
3. Heat the laminate;
4. Store peeled tape.

Figure 18 – Sketch of tape pelling.

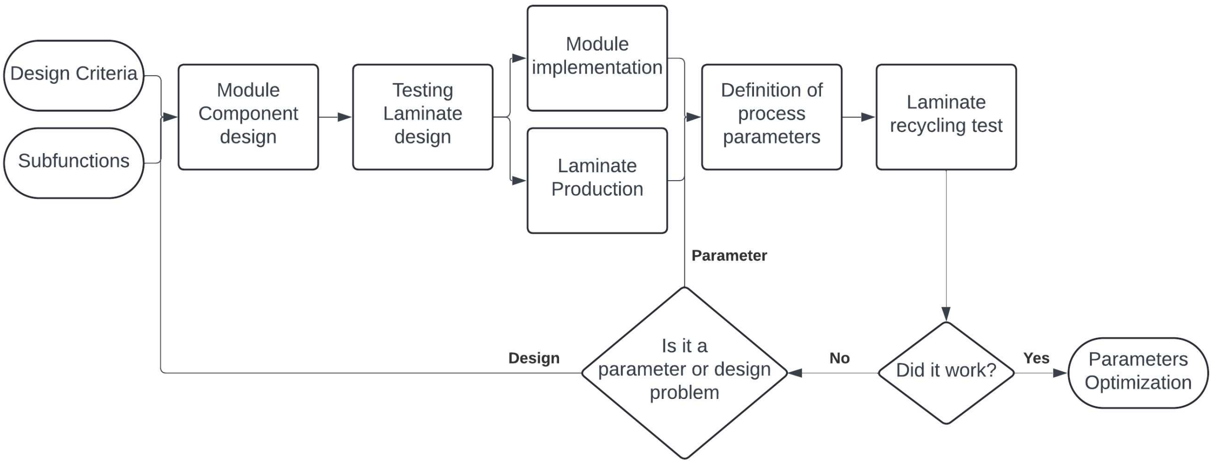


Source: Janssen (2019)

Some possible solutions for the necessary subfunctions can be found. For heating the laminate, a gas torch or laser system would be possible solutions, with the latter being preferred due to already being present in the Prepro2D. A new component will be designed, to separate the peeled tape from the laminates, with basis in currently used norms for the testing of the interlaminar bond of thermoplastics, such as ISO 11343. The storing and generation of the peeling force, will be combined into a single component, which is also present in the machine, being a motorized tape spool, which will generate a torque that will be transferred as tape tension to the tape that is being peeled and will then work as the peeling force.

With all the design criteria selected and the subfunctions determined, the steps necessary for the creation of the module to be used for the validation of the method can be defined. A flowchart of the design process can be seen on figure 19 , starting with the module components, and finishing with the optimization of the process parameters.

Figure 19 – Flowchart of the design process.



Source: Author.

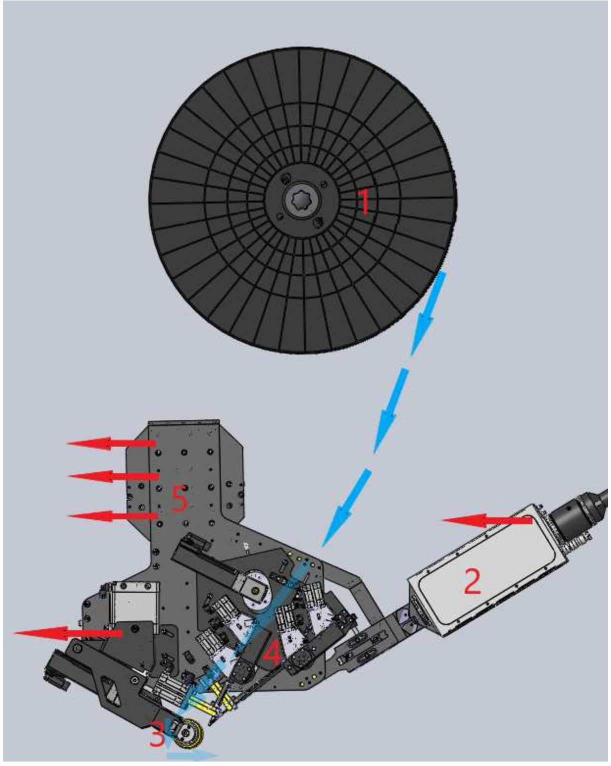
With the overview of the design process defined, the recycling method through the peeling of prepreg tapes from the laminate, the reversal of the LATP process, can be envisioned and the design of the module started.

Some advantages of this method can already be predicted. First, since during the recycling process no cuts will be made to the material, the recycled tape will possess a long fiber length, equal to the component length, this way, the longitudinal properties of the fiber will not be lost. Second, because this implementation will be through the development of a module to be attached to the Prepro2D, it will be easily adapted to other LATP machines, creating an ease of accessibility for its usage.

3.1 MODULE DESIGN

The current LATP module present in the PrePro2D can be seen on figure 20, the different components are numbered, and their functions briefly described. The tape movement is indicated by blue arrows, and the module movement in relation to the laminate by red arrows.

Figure 20 – LATP configuration of the PrePro2D.



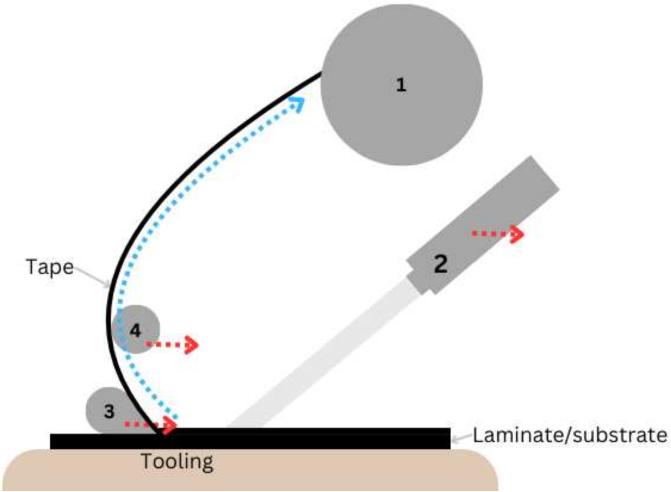
Source: Author.

1. Tape spool - A spool attached to a motor, used to store and feed the tape used during the process.
2. Laser - A laser system used for the heating of the prepreg tape and Laminate, to enable consolidation during tape deposition.
3. Compression roller - Presses the prepreg tape into the laminate, developing intimate contact between them and enabling consolidation.

4. Tape cutting unit - Cuts the prepreg tape at the end of its path, improving automation.
5. Mounting back plate - Serves only a structural purpose, an attachment point for all the necessary mechanisms.

A basic schematic can now be envisioned for the peeling module and can be seen on figure 21, the different components are numbered and described, the tape movement is indicated by blue arrows, and the module movement in relation to the laminate by red arrows. When possible, the components of the LATP module will be reused, as to facilitate the module installation into the system.

Figure 21 – Peeling configuration schematic.



Source: Author.

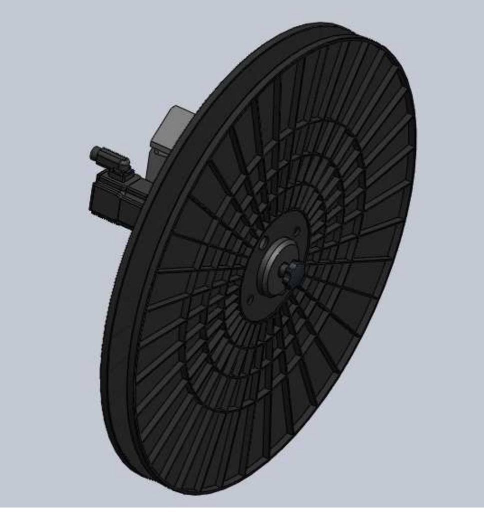
1. Tape spool - Reused from the LATP module, will apply tension on the tape to perform the peeling of the tape.
2. Laser - Reused from the LATP module, will heat the laminate, softening the material and this way enabling the peeling of the tape.
3. Wedge - Newly designed, will serve as a physical barrier to facilitate the separation of the tape from the underneath layer.
4. Roller - New component, its function is to redirect the tape, preventing bending in the peeling region and ensuring contact between the tape and the wedge.

As previously mentioned, some components will be re-utilized from the Prepro2D when possible, but new ones will also need to be designed and either bought or produced. The components will be identified with base in if they are newly designed or already present.

3.1.1 Tape Spool - Reused

The tape spool system consists of a spool attached to a motor, as can be seen on figure 22, in the LATP process, the spool is used to store the tape used during the process, and the motor to feed tape while maintaining a specified tape tension that benefits the process.

Figure 22 – PrePro2D's tape spool.



Source: Author.

In the peeling process, the spool will serve as an attachment point for the to be peeled tape, while the motor will generate a torque in this spool, generating tension in the attached tape, which will work as the peeling arm.

The motor used on the spool system is a low-voltage servomotor of the brand Beckhoff, model AM8122-0F20, and can be seen on the figure 23. It has a maximum torque of 4.06 Nm and maximum angular speed of 2000 rpm (BECKHOFF, 2024b).

Figure 23 – Servomotor AM8122-0F20.

Source: Beckhoff (2024b)

Attached to the motor is the AG2250-+PLE60-M01-5 gear unit also from Beckhoff, this has a gear ratio of 5 (BECKHOFF, 2024a). The spool core, in which the tape will be attached,has a diameter of 160mm. With these values, and equations 1 and 2 we can calculate the maximum tension on the tape that the system will be able to apply.

$$Gearratio = Torque_{output}/Torque_{input} \tag{1}$$

$$Force = Torque/Radius \tag{2}$$

Considering an input torque of 4.06 Nm, and a gear ratio of 5, the output torque will be 20.3 Nm. With a radius of 0.08m, the resulting maximum force will be 253.75 N, which will be transferred to the tape, meaning a maximum tape tension of 253.75 N.

3.1.2 Laser System - Reused

The laser system is composed of a diode Laser by the company Laserline, model LDF 4500-30, which can be seen on figure 24. It has a maximum power of 4000 W, a minimum power of 400 W, a wave length between 940 - 1064 nm. Attached to the laser is Laserline's Zoom Optic OTZ-2, which makes it possible to adjust the laser focus into different shapes and sizes, with the size varying from 12x12 mm^2 up to 80x80 mm^2.

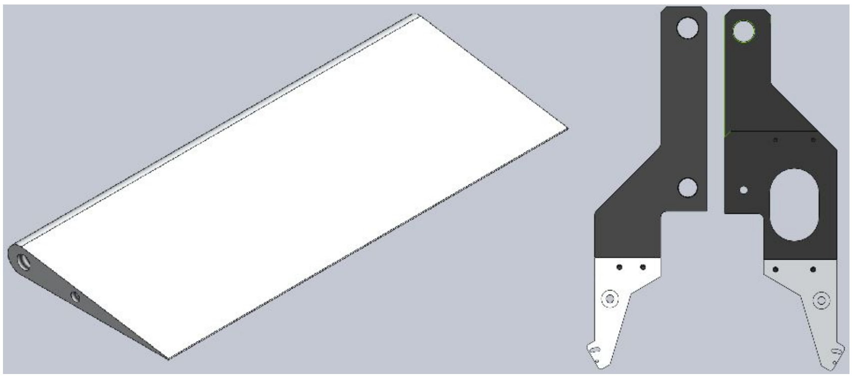
Figure 24 – Laser system LDF 4500-30.

Source: Fraunhofer Institute for Material and Beam Technology IWS (2015)

3.1.3 Wedge - New design

The wedge which is a new component, designed specifically for the peeling method, has the function of separating the tape from the laminate and can be seen on figure 25 alongside its mounting bracket.

Figure 25 – Wedge and mounting brackets.



Source: Author.

The wedge system can be separated into two parts, the first one of them being the wedge itself, which has an angle of 9°, similar to that used in the wedge peel test, in accordance to ISO 11343. It has two screen holes in each side for its mounting, which allows it to be rotated around one of these holes, enabling different wedge angles to be used.

The support bracket is composed of two pieces, one piece for each side of the wedge. These pieces of the bracket, have been separated into 2 components for ease of production. Therefore the support brackets are composed of 4 different components. Their functions is to be mounted onto the Prepro2D connecting and position the wedge. The attachment point for the wedge, allows for a varying mounting angle, between 1° and 31°.

The design of the wedge bracket was achieved by using the support piece for the LATP compression roller as a base, and modifying the design and connection points where the wedge would be assembled. The points which are connected to the Prepro2D were left unchanged and those would still be used, and some extra connection points were kept for the holding of previously used components, even though they would not be used in the recycling process, to remove the need of unplugging them from the machine.

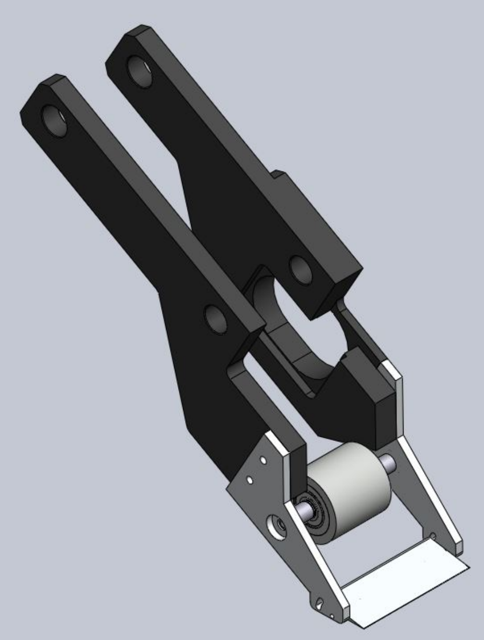
Close to the wedge point in the brackets, two screw clearances were made, for the installation of a freely rotating roller. All the 5 components, 4 from the bracket and the wedge are to be machined in aluminum.

3.1.4 Full Module Assembly - New design

The full peeling module can be assembled, as seen on figure 26, it consists of 7 different pieces: The wedge; 4 support brackets components; A roller with bearings so it can freely rotate; And a shaft to support the roller.

The roller is bought from the company Misumi, model ROERHS40-10-40-T5, it has a diameter of 40mm, length of 40mm, the surface is made from urethane, and

Figure 26 – Peeling module assembly.



Source: Author.

the bearings from steel. Its function is to redirect the tape without any bending and to ensure contact between the surface of the wedge and the tape.

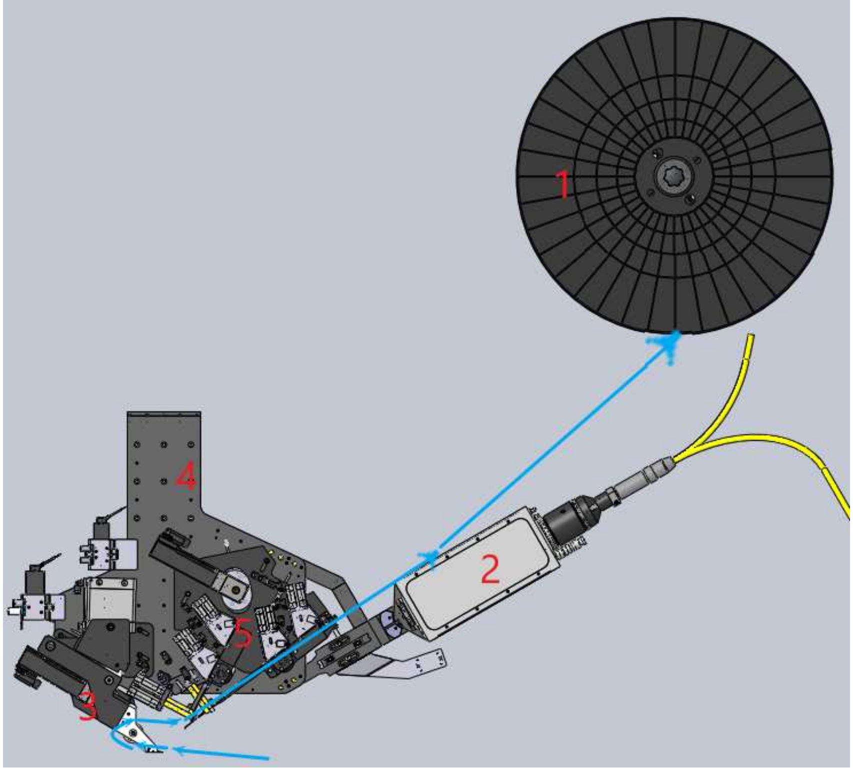
The shaft is a machined piece of stainless steel, it is attached with screws to both sides of the support brackets and is where the roller is mounted. There are two grooves present on the shaft, designed according to DIN (2011), for the mounting of retaining rings to ensure the roller stays in place.

3.1.5 Module Setup on PrePro2D

With all the components function described and their positioning defined, the peeling module can be assembled on top of the back plate, as seen on figure 27, the parts are numbered and the tape path shown by blue arrows. The difference between this setup and the LATP setup is only the swap between the compression roller module and the peeling module.

1. Tape spool - The tape spool has not been changed, and its position remain the same as the LATP module
2. Laser - The laser has not been changed, and its position remain the same as the LATP module.
3. Peeling wedge module - The newly designed module has been installed into the compression roller position. Its attachment points are the same as the compression roller, so a 1 to 1 swap is possible without changes to the back plate.
4. Mounting back plate - The back plate has been left unchanged.

Figure 27 – Peeling module setup.



Source: Author.

5. Deactivated tape cutting unit.

The tape will be guided through the deactivated tape cutting unit, as to remove the need for the removal of the tape cutting unit. The position of the tip of the wedge is the same as of the nip point of the previously used compression roller, this ensures that the peeling happens at the focus distance of the laser.

The direction of the wedge and therefore the movement direction of the process has been chosen this way, because in the opposite direction the wedge would be in the path of the laser. The peeling wedge is attached to a pneumatic cylinder which is attached to the back plate, this was already present in the LATP setup, enabling the use of compression force on the wedge.

3.2 LAMINATE DESIGN

With the module complete and its physical limitations known, the laminates necessary for the testing of the peeling method and its validation can be designed.

First, the material needs to be defined. CF is the chosen fiber type, due to its higher tensile strength when compared to others such as GF, because of the the tension applied during the process. A thermoplastic matrix is needed, due to the necessity of the material being able to repetitively melt and consolidate. With these requirements in mind, and considering that it is promptly available, the UD tape Akulon PA6-HC10 is used, its properties can be found on table 3.

Table 3 – Akulon PA6-HC10 UD Properties.

Property	Value
Tape width	25mm
Tape Thickness	0.25mm
Fiber content	38.5%
Tensile modulus	110 GPa
Tensile Strength	1100 MPa
Melting Temperature	220°C

Source: DSM (2019)

The geometric characteristics also need to be defined. For simplicity it will be a square flat laminate, of 400mm x 400mm, therefore each layer will be composed of 16 tape segments. Five layers are used, the bottom four will serve to give support to the laminate, while the top layer will be peeled. Each layer's fiber orientation can be seen on table 4 alongside any different characteristics.

Table 4 – Laminate fiber orientation.

Layer	Fiber Orientation	Different characteristic
Layer 1	0°	None
Layer 2	90°	None
Layer 3	0°	None
Layer 4	90°	None
Layer 5	0°	Loose ends on one side.

Source: Author.

For the peeling process, there is a need for loose ends on one side of the layers that will be peeled. These will serve as attachment points to the tape spool and used for the transmission of tension necessary for the process. Therefore at least an extra 2.25 m of unconsolidated tape at the end of the 16 tape segments of the top layer is necessary.

Different parameters for the production of the laminates can be used, resulting in different qualities and levels of consolidation. Some of these parameters are the tape laying speed, laser power, laser angle and the temperature of the table,on top of which the laminate is produced. For the testing of the module, different parameters are used on the production of the laminates, which can be seen on table 5, resulting in different levels of consolidation.

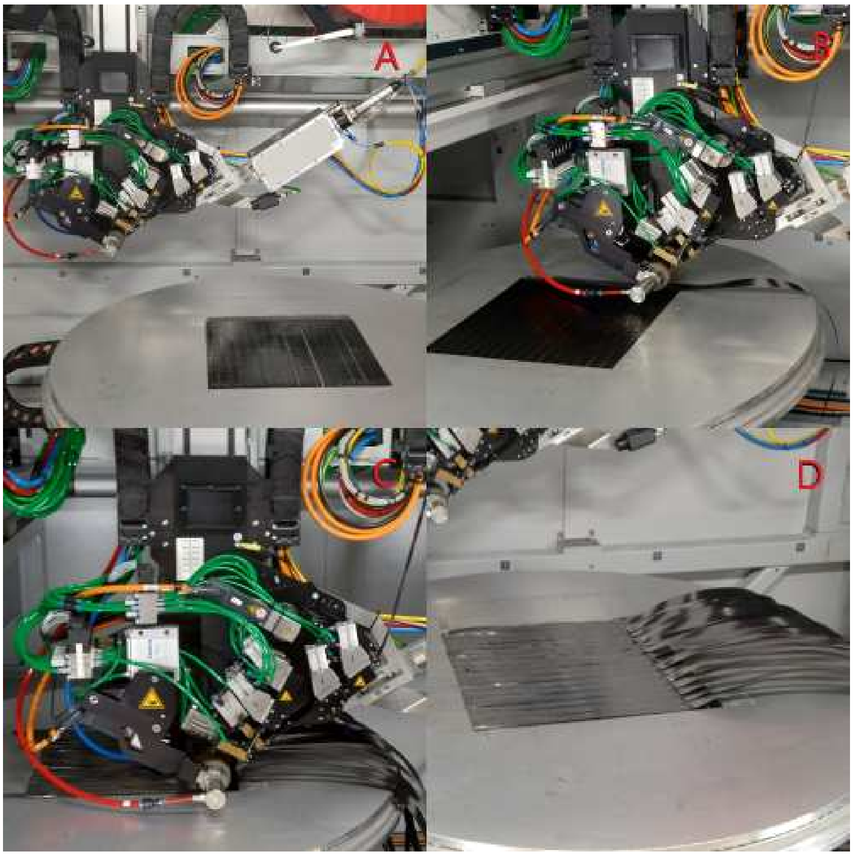
Table 5 – Laminate production parameters.

	Type 1	Type 2	Type 3
Laser Power	1300W	700W	750W
Tape laying speed	500mm/s	250mm/s	250mm/s
Laser angle	-3°	+1°	+1°
Table Temperature	135°C	140°C	140°C
Notes		Laser power at 550W on first layer	Laser power at 575W on first layer

Source: Author.

The process for the production of the test laminates start with the laying of the bottom 4 layers, resulting in the laminate shown in figure 28A. The tape cutting unit is then deactivated, and the top layer is then laid down, with the tape being cut manually to ensure the loose end length. The laminate after the 1^{st} tape segment of the top layer can be seen on figure 28B, and after the 16^{th} on figure 28C. The full test laminate can be seen on figure 28D.

Figure 28 – Test laminate production steps.



Source: Author.

3.3 LAMINATE PRODUCTION

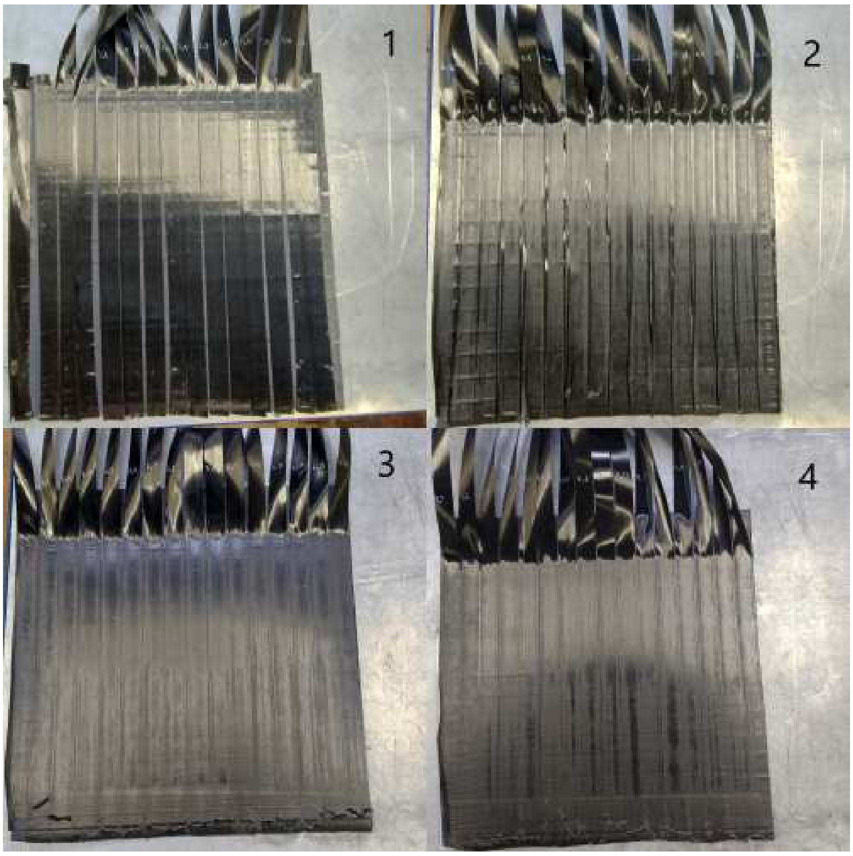
Utilizing the parameters from the table 5 and the previously described process, 4 test laminates were made. These laminates can be seen on figure 29, and their details on table 6. The tape segments are numbered, for better identification after their removal.

Table 6 – Produced laminates.

Laminate number	Laminate Type	Observations
Laminate 1	Type 1	Only 13 tape segments successfully consolidated.
Laminate 2	Type 2	Tapes not consolidated on the edges.
Laminate 3	Type 3	
Laminate 4	Type 3	

Source: Author.

Figure 29 – Test laminates.



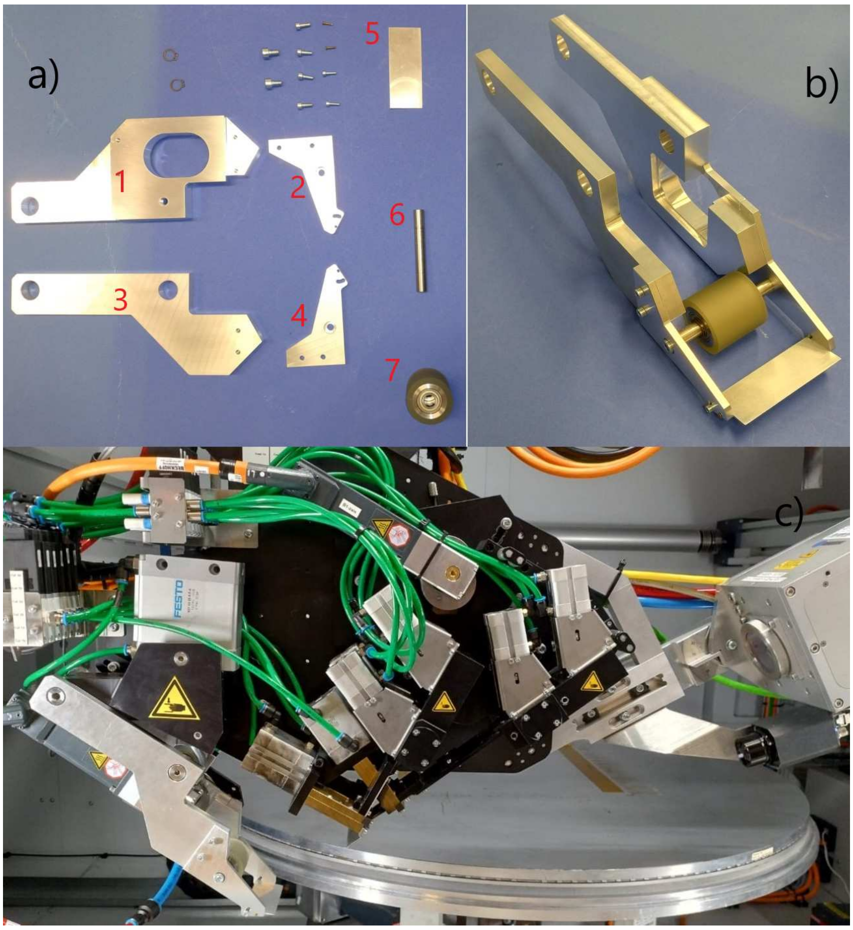
Source: Author.

Laminates 1 and 2 apparent a lower level of consolidation, which in turn should make the peeling process easier, because of that they will be used during the first tests for the definition of working process parameters.

3.4 MODULE INSTALLATION

With all the necessary components being available, as shown on figure 30a), alongside some screws and 2 retaining rings, the module can be assembled as shown on figure 30b). With the necessary test laminates produced, the LATP module can be removed from the machine, and the newly assembled peeling module installed in its place, as show in figure 30c).

Figure 30 – Module components and installation.



Source: Author.

The components shown in figure 30a) are numbered, and can be seen bellow:

- 1 and 2: Left side of the support bracket.
- 3 and 4: Right side of the support bracket.
- 5: Wedge.
- 6: Shaft for the redirection roller.
- 7: Roller.

The module is attached to a pneumatic cylinder model DZF-50-25-A-P-A by Festo, it has a maximum functioning pressure of 1 MPa. It is usually used for the compression force during LATP processes, but can also be used to apply a force at the edge of the wedge, to ensure its contact with the underneath laminate.

This force can be calculated with equations 3 and 4. Considering a equivalent piston diameter of 25mm, a lever distance on the cylinder of 116.2 mm and on the wedge of 207.1 mm.

$$Force = Pressure \times \pi \times (CylinderDiameter)^2/4 \tag{3}$$

$$WedgeForce = (CylinderDistance \times CylinderForce)/WedgeDistance \tag{4}$$

As a result, the vertical force in newtons on the wedge is 275.42 times the current pressure in mega pascal on the cylinder.

3.5 PROCESS PARAMETERS

There are 6 parameters that dictate this process and they affect 2 important properties. The first one is the temperature of the tape that is going to be peeled, which we want above its melting temperature but not hot enough to burn the matrix. The second one is the peeling force, which is the force necessary to peel the tape, it is dependent on the angle of said force and temperature of the material. The parameters are as follows:

1. Laser power - given in watts, is the amount of energy irradiated from the laser system onto the tape, it affects the process temperature. An increase in laser power means and increase in temperature, and vice versa.
2. Processing speed - given in mm/s, is the speed in which the tape is removed from the underneath layer, it affects the process temperature. An increase in processing speed means a decrease in temperature, and vice versa.
3. Laser angle - given in degrees, is the angle of the laser positioning. During LATP processes it dictates how much of the laser is irradiated into the tape and how much into the substrate. For the peeling, it defines how much of the irradiation goes into the tape that is about to be peeled and the tape that has just been peeled. It is important for the laser to be pointed mostly at the substrate, as there is no reason to heat the already peeled tape. The more negative the angle, more heat will be received by the part of the tape that is not peeled yet.
4. Wedge compression force - is the force with which the wedge's edge is pushed vertically against the substrate. It is used to ensure the contact between the edge and the laminate during the whole process. The greater the compression force, the harder it will be to separate the wedge from the laminate.
5. Wedge angle - defines at what angle the peeling force will be applied into the laminate. The increase in the wedge angle causes the peeling force to get closer

to 90°, therefore causing a reduction in the necessary peeling force. On the downside a greater wedge angle, will increase the bending of the tape, risking damage to the fibers.

6. Tape tension - will act as the peeling force. In the current setup it can not be configured, and is automatically adjusted by the system to match the processing speed. With its maximum values defined by its physical limitations.

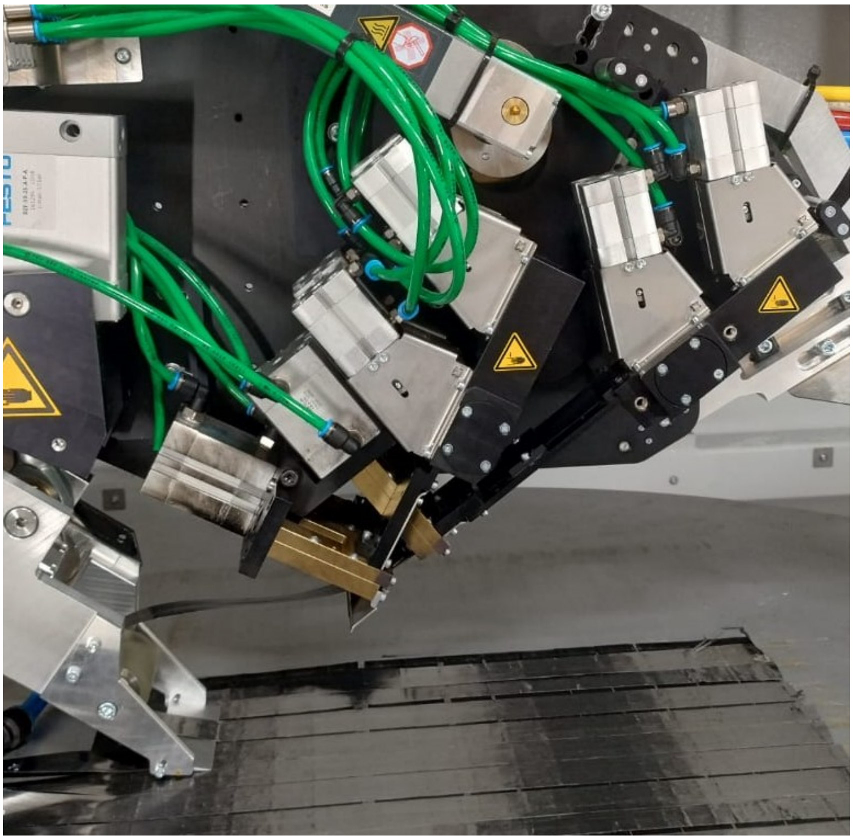
Different parameters can be varied and tested, first with the purpose of finding a functioning set of values, and after for the optimization of the process. These values can be tabled, to better understand their effect on the process, and decisions made on how to improve the testing.

4 RESULTS

4.1 FIRST LAMINATE

For the first laminate, the objective was finding working parameters, the setup was assembled as shown in figure 31. The tape was guided on top of the wedge, around the roller, through the guiding element, and connected into the spool.

Figure 31 – Peeling module test setup.



Source: Author.

The tests start with the last tape laid on the laminate, in this case tape 13, in case there is any overlap, to guarantee the peeled tape is on top. The starting parameters of the test can be seen on table 7.

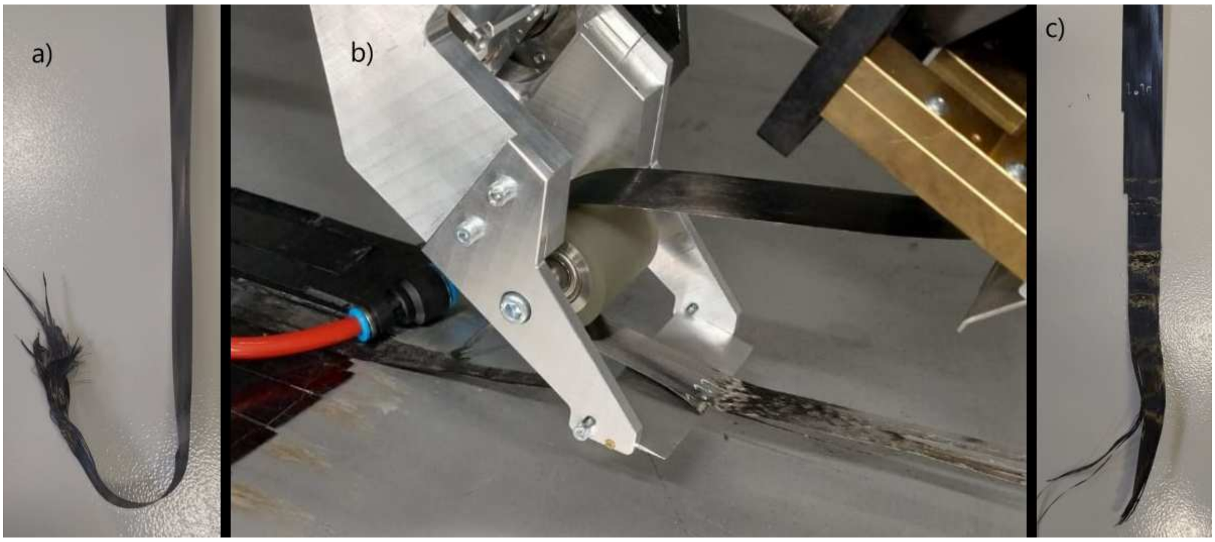
Table 7 – First laminate - parameters for tape 10 through 13.

Tape n°	Laser power	Processing speed	Laser angle	Compression force	Wedge angle
Tape 13	400 W	100 mm/s	1°	0	1°
Tape 11	400 W	100 mm/s	-2°	27.54 N	1°
Tape 10	400 W	100 mm/s	-2°	55.08 N	1°

Source: Author.

- Tape 13: The fibers got torn off right in the beginning of the pulling and dragged through the laminate, as can be seen on figure 32a). The reason for this could be because the laser angle was too high, heating the tape and not the laminate, and there was no compression force ensuring contact with the wedge. For the next tape the compression force was turned on, and the laser angle reduced, as seen on table 7.

Figure 32 – First Laminate - Tape 10, 11 and 13.



Source: Author.

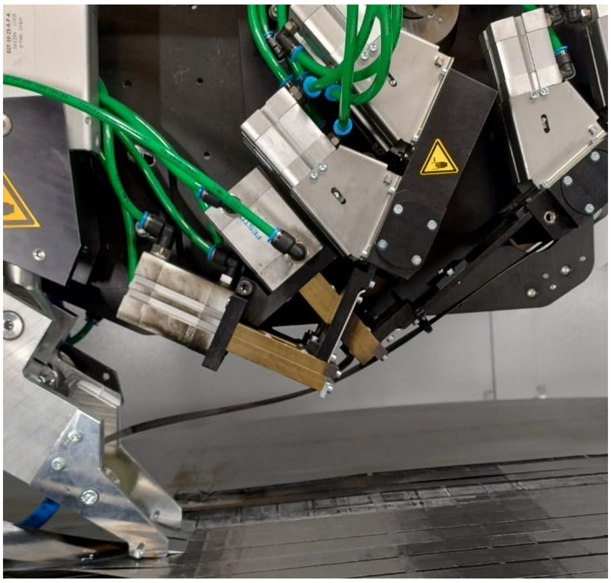
- Tape 12: This tape was removed from the test, due to a big overlap with the leftover of tape 13, and the results would not be a good representation of a well produced laminate.
- Tape 11: During the peeling process, the tape folded, slid under the wedge and then got re-consolidated on top of itself, as can be seen on figure 32b). To fix this problem for tape 10, the compression force was increased, making it harder for the tape to get stuck under the wedge, the new parameters can be seen on table 7.

- Tape 10: The results which can be seen on figure 32c), were already more promising, with a decent amount of tape being peeled. During this peeling, it was noticed that the peeled tape would get stuck in the guiding mechanism.

The tape would get stuck because the gaps in the guiding mechanism were designed for new tapes, and therefore due to the deformations that happened to the peeled tape, it would not fit the gaps in the guiding element anymore.

Due to getting stuck, the tape tension would not be transmitted to the peeling region, and the peeling force would be lost. To fix that, the tape would be guided around the element, as can be seen on figure 33. The drawback of this workaround is that nothing would force the tape to be kept straight, allowing for the possibility of an uneven tape tension along the tape width.

Figure 33 – Workaround for the guiding element.



Source: Author.

- Tape 9: was unusable, due to an error while preparing for the peeling.

Because of the main change in one of the mechanisms of the process, the parameters were kept the same for tape 8, as can be seen on table 8, the only difference is the tape going around the outside of the guiding element.

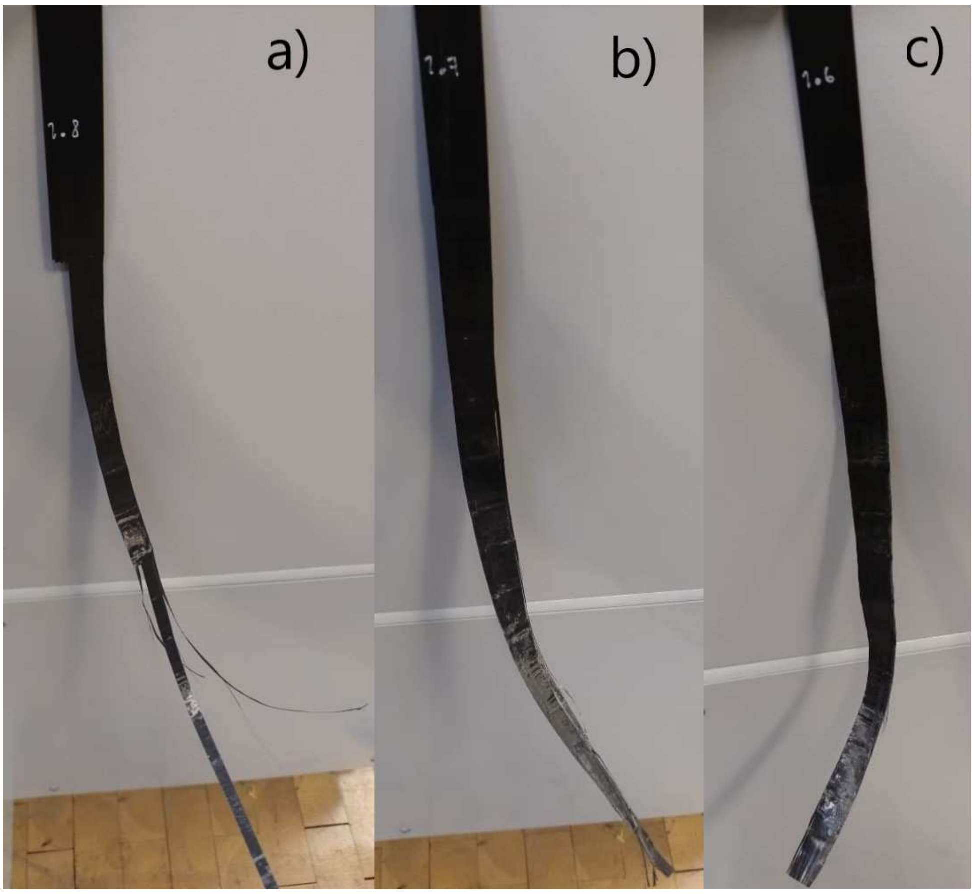
Table 8 – First laminate - parameters for tape 6 through 8.

Tape n°	Laser power	Processing speed	Laser angle	Compression force	Wedge angle
Tape 8	400 W	100 mm/s	-2°	55.08 N	1°
Tape 7	400 W	100 mm/s	-2°	55.08 N	1°
Tape 6	400 W	100 mm/s	-2°	55.08 N	1°

Source: Author.

- Tape 8: The peeling showed good results, as can be seen on figure 34a), with parts of the tape being peeled the whole length of the laminate. But some fibers were torn out at the beginning of the peeling due tear in the tape before the process began.

Figure 34 – First Laminate - Tape 6,7 and 8.



Source: Author.

- Tape 7: the parameters were the same as tape 8, to test repeatability. The whole tape was peeled off for the majority of the length, which can be seen on figure 35 in comparison with the laminate length. Some fibers were lost only close to the end of the laminate, shown in figure 34b).

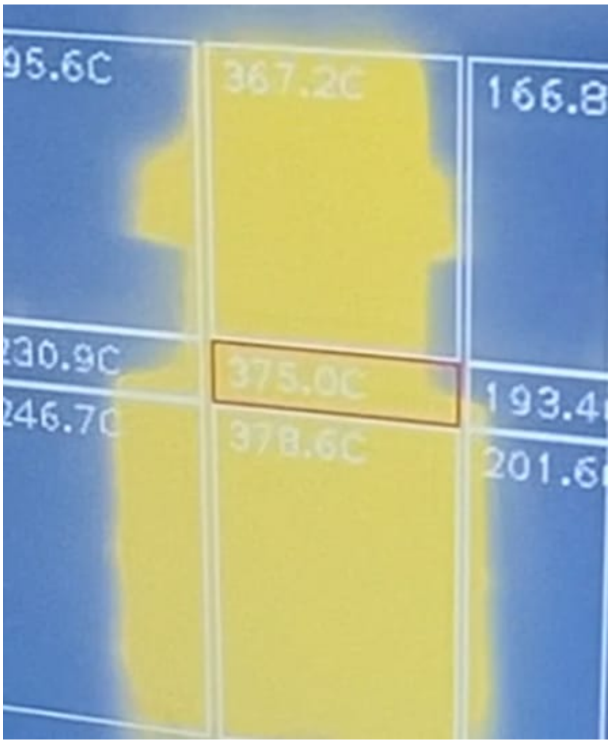
Figure 35 – Peeled tape 7 on first laminate.

Source: Author.

- Tape 6:the parameters were kept the same, to again ensure process repeatability, and the results were similar to tape 7, seen in figure 34c).

During the peeling of tape 6,7 and 8 the process was recorded with a thermal camera, one frame of the recording can be seen on figure 36. It is observed that the laminate temperature during the process is around 370°C, well above the necessary 220°C , but not hot enough to burn the thermoplastic matrix.

Figure 36 – Thermal imaging for peeling process.



Source: Author.

For the next tape, the same parameters were used and are show in table 9. Again to test if the results are consistent using parameters that are showing positive results.

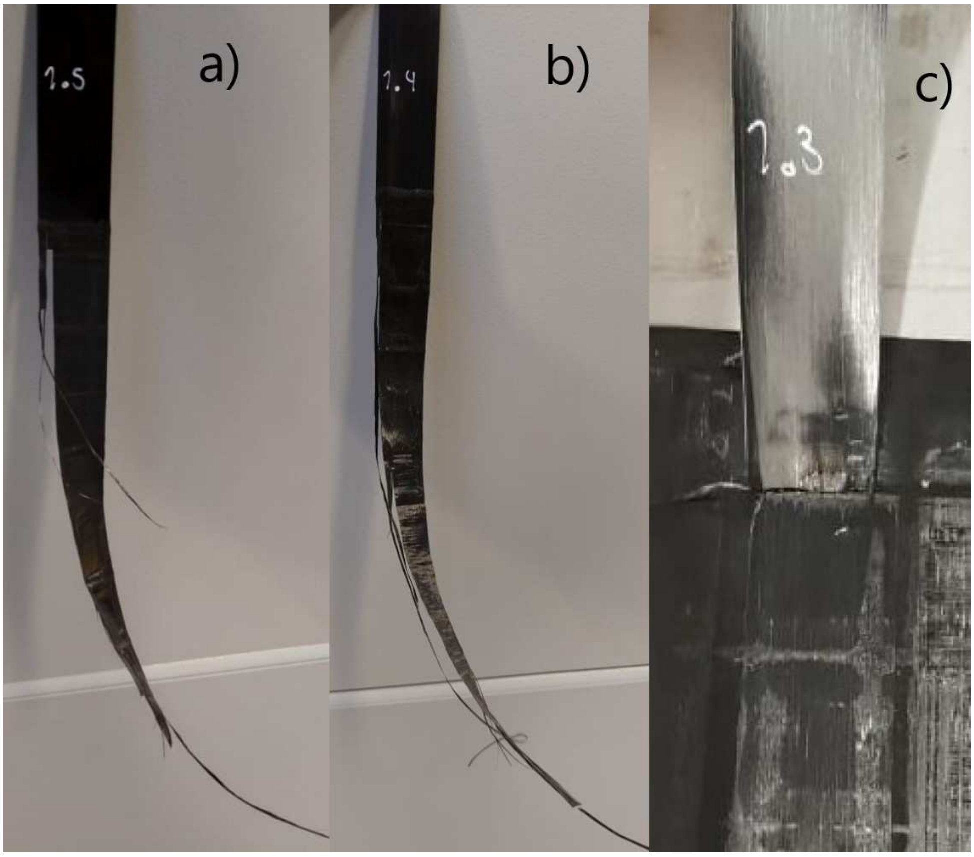
Table 9 – First laminate - parameters for tape 3 through 5.

Tape n°	Laser power	Processing speed	Laser angle	Compression force	Wedge angle
Tape 5	400 W	100 mm/s	-2°	55.08 N	1°
Tape 4	400 W	100 mm/s	-2°	68.85 N	1°
Tape 3	400 W	100 mm/s	-2°	82.62 N	1°

Source: Author.

- Tape 5: This time, the tape teared around the middle of the laminate, with a short length for the peeled fibers as seen on figure 37a). This could be because the wedge wasn't positioned well and lost contact with the laminate during the process.

Figure 37 – First Laminate - Tape 3,4 and 5.



Source: Author.

- Tape 4: To try and fix the lost contact with the wedge, the compression force was increased to 25%, as show in the parameters in table 9. This increase didn't improve the peeling and the result is similar to that of tape 5 as shown in figure 37b).

- Tape 3: A further increase in compression was made for the , but the results were not satisfactory, and the tape got cut by the wedge in the beginning of the process. which can be seen in figure 37c).
- Tapes 1 and 2: The tapes were not tested, due to a big overlap and uneven surface in both of them, therefore the peeling of laminate 1 was complete, and the leftover of the peeled first laminate can be seen on figure 38.

Figure 38 – First laminate after peeling.

Source: Author.

During the peeling of this first laminate, the best results were achieved with a laser power of 400 W, processing speed of 100 mm/s, wedge angle of 1°, laser angle of -2° and compression force of 55,08 N. Increasing the compression force further than this, didn't show any improvement.

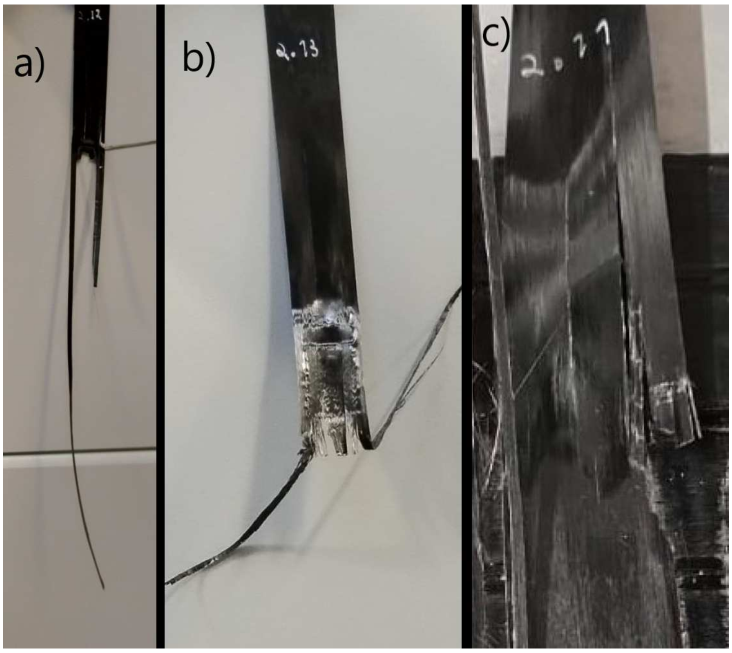
Even though the consolidation on this laminate was not the best, on 3 occasions almost the whole segment of tape was peeled, and these parameters are a good starting point for the next laminates.

4.2 SECOND LAMINATE

The second laminate was the one in which the edges are not consolidated. The starting parameters are those defined at the end of the first laminate. Preparing the testing is kept the same.

Because of the bad consolidation and fully unconsolidated edges of the tapes, some problems arose during their peeling. The tape tension was getting concentrated in the not consolidated regions and because of that the middle of the tape had no peeling force. This caused the middle region of the tape to get cut by the wedge as can be seen on the tapes 12 and 13 shown in figure 39a) and 39b).

Figure 39 – Second laminate - Tapes 11,12 and 13.



Source: Author.

The edges of the tapes were also getting caught in the peeling process of the neighboring tapes, and ripping the segment from which they came from. So the peeling of one tape would damage and render useless the tape next to it, as can be seen on the tape 11, shown on figure 39c), which was damaged during the peeling of tape 12.

For these reasons, the results from the second laminate are not valid to further define a suitable process windows, but they show the necessity of high quality laminates to test the recycling process.

Even thought the results are not valid, an important observation was made during this laminate. Which was that because of a design error, the tip of the support bracket was lower than that of the wedge. For that reason, the contact point between the laminate and the module would be in its mounting, and a gap originated between the wedge and the laminate, allowing the tape tape to slide under it.

To fix this problem, the wedge angle was increased by around 2°, as show in figure 40. Giving the wedge enough clearance as to ensure its full contact with the laminate.

Figure 40 – Wedge positioning with increased angle.

Source: Author.

4.3 THIRD LAMINATE

The third laminate test setup, starts with the same parameters previously defined at the end of the first laminate. With the tape being guided around the peeling unite, and the wedge angle changed to 3°.

This laminate presented the best consolidation quality, so its peeling should be more challenging, but with said quality comes an even surface and consolidation through all its surface.

The first tape peeled was number 16, the parameters used can be seen on table 10, and it will serve as a baseline for the next tapes.

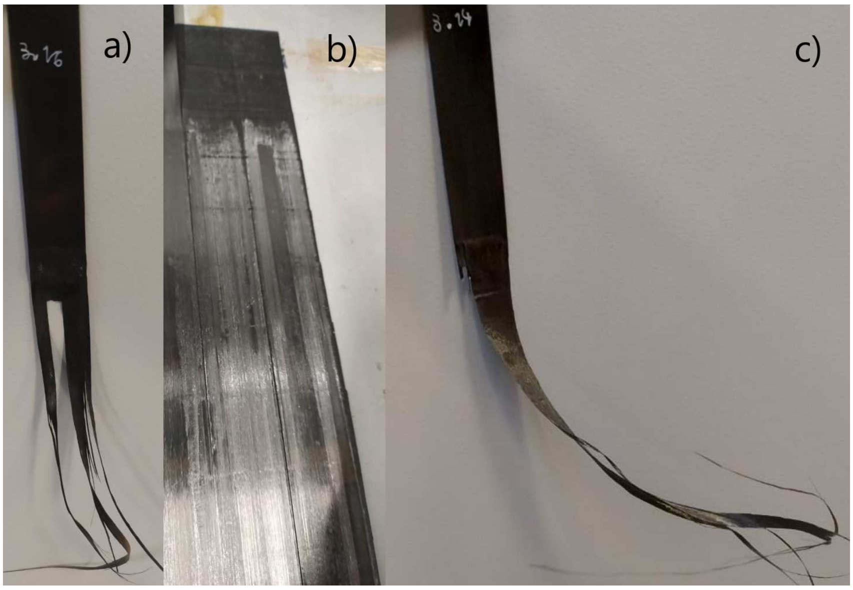
Table 10 – Third laminate - parameters for tape 14 through 16.

Tape n°	Laser power	Processing speed	Laser angle	Compression force	Wedge angle
Tape 16	400 W	100 mm/s	-2°	55.08 N	3°
Tape 15	500 W	100 mm/s	-2°	55.08 N	3°
Tape 14	400 W	75 mm/s	-2°	55.08 N	3°

Source: Author.

- Tape 16: the fibers separated in the beginning of the process, and some were peeled until close to the middle of the laminate, while some were cut short, as can be seen on figure 41a). For the next attempts single parameter will be changed, to verify their effect on the peeling.

Figure 41 – First laminate - Tapes 14,15 and 16.



Source: Author.

- Tape 15: Laser power was increased, causing an increase in the process temperature, the parameters can be seen on table 10. Some of the tape was peeled until the middle of the laminate, with the left side of the tape being cut short. The spot the tape left in the laminate can be seen on figure 41b).
- Tape 14: Process speed was reduced, having a similar effect to the previous tape, the parameters can be seen on table 10. The results were also similar to the previous tape, and the resulting tape can be seen on figure 41c).
- Tape 13: An increase in compression force was tried again, to verify if it would help in stop parts of the tape being cut in the beginning. The parameters for tape 13 can be seen on table 11, and no changes were observed in the result, with the left side still being cut short.

Table 11 – Third laminate - parameters for tape 12 and 13.

Tape n°	Laser power	Processing speed	Laser angle	Compression force	Wedge angle
Tape 13	400 W	100 mm/s	-2°	82.62 N	3°
Tape 12	500 W	75 mm/s	-2°	55.08 N	3°

Source: Author.

- Tape 12: ON this peeling attempt both the laser power were increased and the processing speed decreasing, show in table 11, both compounding on an increase in temperature. This caused the tape to get to hot, and burn the material.

For the next 3 tapes, number 11, 10 and 9, an decrease in temperature was tested, since the laser power cannot go lower than 400 W, that was done by increasing the processing speed. These new parameters can be seen on table 12.

Table 12 – Third laminate - parameters for tape 9 through 11.

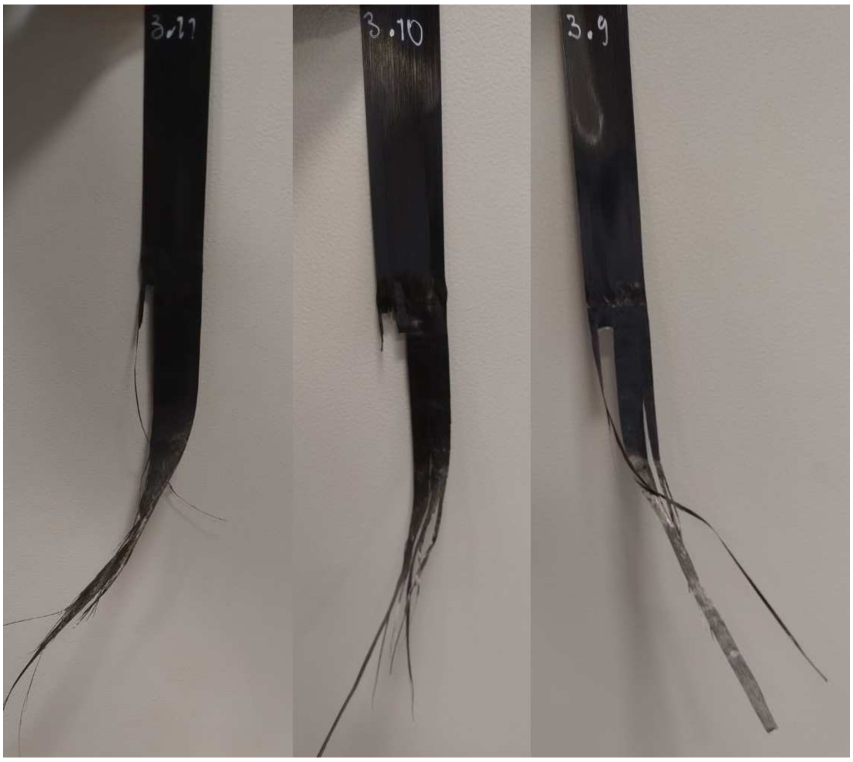
Tape n°	Laser power	Processing speed	Laser angle	Compression force	Wedge angle
Tape 11	400 W	125 mm/s	-2°	55.08 N	3°
Tape 10	400 W	150 mm/s	-2°	55.08 N	3°
Tape 9	400 W	150 mm/s	-2°	55.08 N	3°

Source: Author.

The 3 peeled tapes, can be seen on figure 42.

- Tape 11: The results were similar to those before it, with a decent section of the tape being peeled until the middle of the laminate, and the left section of it cut short.

Figure 42 – First laminate - Tapes 9, 10 and 11.



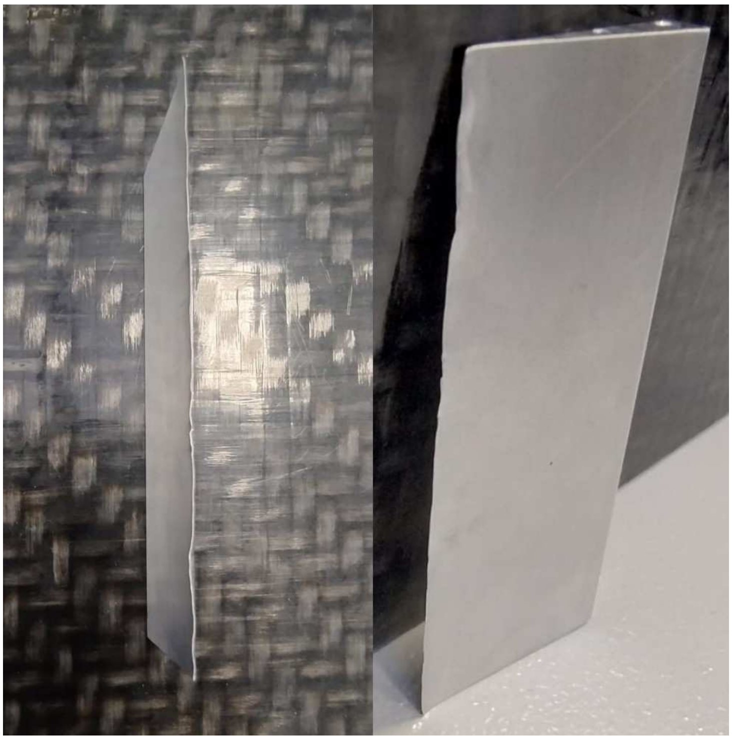
Source: Author.

- Tape 10: a further increase in velocity, and therefore decrease in temperature, was applied. An error occurred in the peeling of tape 10, during which the laser was on for a moment before the movement started, burning the peeling section. For that reason, tape 9 was tested with the same parameters.

- Tape 9: Close to half the tape, on the left side, was cut short and the rest of it was peeled by one third of the laminate extension. Similar results were obtained on the previous tape.

On all the tapes of the third laminate, it was noticed that the left section of the tape was always being cut short. While inspecting the wedge, it was noticed that its edge was damaged during previous peeling processes, as showcased in figure 43, in which dents can be seen on the edge, and that could be the reason the tape was being cut short.

Figure 43 – Damaged wedge after peeling attempts.



Source: Author.

Because of this damage on the wedge's edge, the testing process needed to be stopped, as there is no way of differentiating if the process not working is because of the parameters, design or the edge's defects. For future attempts a new edge would need to be made, this time of a more durable material than aluminum.

4.4 TESTING SUMMARY

While the testing had to be stopped prematurely valuable insights were obtained with each laminate. The results for each laminate, are summarized on bellow, showing the problems encountered in each of them, permanent fixes necessary for optimal functioning and the temporary solutions found so that the testing could continue.

- First Laminate:
    - The tape would get stuck in the guiding element, and tension would not be transferred to the peeling region. As a workaround, the tape was guided around the element, but in the future changes need to be made by enlarging the gaps in the guiding component.
- Second Laminate:
    - Not enough clearance at the bottom of the support bracket, interfering with the contact between the edge and the substrate. An increase in the wedge angle solved the problem momentarily, but there is a need for the removal of some material on the bottom of the bracket.
    - Unconsolidated regions would cause an absence in peeling force in the middle of the tapes, showing the necessity of high quality laminates for the testing.
    - Unconsolidated wedges would also cause interference with the neighboring tapes, a future improvement on this would be a wedge with a smaller width.
- Third Laminate:
    - Damage to the wedge's edge was noticed, possibly damaging the tape during the peeling process, the testing had to be stopped for this reason, but in the future wedges made of more durable materials are important so they won't be damaged.

While fully optimized parameters were not found, laser power equals 400 W, processing speed of 100 mm/s, compression force of 55 N and most of the laser's irradiation direct at the substrate seems to be good starting points. Further increase in the compression force didn't appear to have any impact in the results.

5 CONCLUSION

In this work, currently used recycling methods for FRPs were analyzed. A recycling module compatible with the Prepro2d was designed, its components detailed and the laminates necessary for its testing made. The variable parameters necessary for the process were defined, and tested with the intent to test the module and find working parameters.

While working parameters were fully defined, and the module was not fully functional, the results were promising, with almost full tapes being peeled on the lower quality laminates, and decent sections of tape in the higher quality laminates. This exhibits the validity of the method but that further work is necessary.

The region for the function parameters seems to be around 400 W for the laser power and 100 mm/s for the processing speed, which achieves decent temperatures. Suitable compression force appear to be around 55 N, and increasing it above that value doesn't help the process. Having most of the laser irradiation directed at the substrate is also an important factor.

Some factors that negatively impact the peeling process, are an uneven consolidation in the laminate, and tears in the tape close to the peeling region, due to the creation of an uneven tension distribution across the tape, thus implying the necessity of high quality laminates.

Some problems in the design of the module arose during testing, and those need to be fixed before further tests. The last one of these, damage to the wedge's edge caused the current set of tests to be stopped prematurely, due to the possibly damaging the tape. The corrections necessary for the improvement of the process are as follows:

1. Changes to the guiding element, widening the gaps in which the tape fits through, so that the peeled tapes do not get stuck.
2. Removal of some material in the lower part of the support bracket, as to give the wedge more clearance, ensure the edge's contact with the laminate.
3. Reduction in the wedge's width to reduce the interference with neighboring tapes.
4. Configurable tape tension would allow for a better understanding of the parameter on the process.
5. Having the wedge made of a material more durable than aluminum, such as steel, is essential to guarantee that it won't be damaged during the process.

In conclusion, while the results for the peeling method and its method are promising, problems to the current design were identified and fixes need to be made to it to ensure better functioning.

Future work on this subject could include the implementation of the aforementioned changes, and further testing of the module. The definition and optimization of working parameters. Testing the method with different materials, both for the matrix and the fibers. And lastly how the process affects the recycled fibers mechanical properties.

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