Use of Aerospace thermoplastic composite production waste

Designing new applications through reshaping of thermoplastic composite strips

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Delft University of Technology

TUDelft

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by

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Cover Image: Laminate off-cut photographed in the sunlight on the Delft University of Technology campus

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Preface

This thesis project marks the conclusion of my time as a student at the Delft University of Technology, completing both a Master of Science degree in Aerospace Engineering at the faculty of Aerospace Engineering and in Integrated Product Design from the faculty of Industrial Design Engineering.

I gained the first experience in composite material design and manufacturing through my time at Delft Aerospace Rocket Engineering (DARE), and this has been interest of mine ever since. In my time at the faculty of Industrial Design Engineering, I became interested in the field of sustainable design engineering, especially regarding the circular use of materials in design. Therefore, I set up a conversation with Jelle Joustra in 2021, to explore the idea of doing a thesis project related to circular design using composite materials. Over the course of the following months the idea of combining both Master programmes in a single thesis took shape, and was officially started in September of 2022.

This thesis project would not have been able to be initiated were it not for the support of my graduation committee: Ruud Balkenende, Clemens Dransfeld and Bilim Atli-Veltin. Ruud, thank you for suggesting the idea of combining both Master programmes in a single thesis, and for your support initiating this. I thoroughly appreciated you taking the time to provide valuable feedback and support throughout the project. Clemens, thank you for making it possible to incorporate the Aerospace Engineering Master programme in this thesis, and your support along the way. I am amazed by your abilities in the field of engineering and design, the clear feedback that you give, and how you attempt to push me out of my comfort zone. Bilim, thank you for providing this project with the production waste material and connections to aerospace material manufacturers. Without the composite waste material this project not have the same outcome, and I appreciated your feedback on the thesis throughout. Apart from my thesis committee I would also like to extend my gratitude towards Cristiano Alves and Guillaume Ratouit, thank you for providing me with the material for the project and help with any follow-up questions. Special mention also to Jelle Joustra, for your support when I got stuck during the project, and needed another perspective.

I would also like to thank my friends and families for their support. To my family and friends, thank you for providing unconditional support during the difficult parts of the project, your support really helped me push through and finalise the project. I would like to especially thank my girlfriend Eda Karaosmanoglu for putting up with me this past year. Without your love and support I would have never been able to push my own boundaries, and I am eternally grateful for your support.

Sam Lonis
Delft, August 2023

Summary

This project aimed to explore how designers and engineers can design new applications from aerospace thermoplastic composite production waste material.

The first phase of the project explored the materials and production processes used for thermoplastic composite parts for the Aerospace industry, and was finalised with a selection of a production waste type for the remainder of the project. Laminate off-cuts were chosen as the material for this project as these would be available within the time-frame of the project, are recurring from the production process, had little contamination and were in a multiply consolidated form.

The second phase of the project explored what information would be required from the material throughout the design process, and derived a design vision and criteria for the two design processes followed. The design criteria for the functional design dictated that this should be easily adaptable to the varying geometry of the material, easy to manufacture with the available tooling, have a high structural performance and feature an easily adaptable functionality. A design vision was established for the second design process which aimed “To stimulate creative thinking by designers and engineers about the use of thermoplastic laminate off-cuts, by creating a product that grabs their attention, is relevant to them and conveys a strong message about the potential use of the material.”.

In the third phase both design processes were executed, where the functional design processes focused on the shaping possibilities of the material and its mechanical properties. This design process resulted in the design of an adaptable structural member, where the laminate off-cuts can be easily shaped in a new form that changes the properties of the structural member. The second design process also incorporated the aesthetic properties and perception of the material, and resulted in a demonstrator bridge design. This demonstrator bridge design features structural elements made out of laminate off-cuts, and has aesthetic elements that demonstrate the shaping possibilities and functionality of the material, whilst making the aesthetic of the bridge appear streamlined.

The fourth phase evaluated the outcomes of the design processes according to the initially defined aims and criteria, and reflected on the design process used. Here it was concluded that the structural member design meets its criteria in theory, and that the bridge demonstrator design does help the target group in the exploration of new applications for the laminate off-cuts.

As such, it can be concluded that designers and engineers can utilise the value of the material for purely functional applications, but that it can also be used to shape the personality of a new product application. The process of designing new applications revolves around uncovering the value of the material by exploring the material characteristics and processing possibilities, and connecting this to new applications through a design vision.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
CFRP	Carbon Fibre Reiforced Plastic
EASA	European Union Aviation Safety Agency
EOL	End-Of-Life
ILT	Inspectie Leefomgeving en Transport
LM-PAEK	Low-Melt Poly Aryl Ether Ketone
MPa	MegaPascal
MRO	Maintenance Repair & Overhaul
OEM	Original Equipment Manufacturer
PPS	PolyPhenylene Sulfide
QI	Quasi-Isotropic
UD	Uni-Directional

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1 Introduction

1.1. Background

The emissions of the global aviation sector (passenger and transport) are estimated to be 2.4 % of the global anthropogenic CO_2 emissions [1][2], and are expected to triple by 2050 compared to 2015 [3]. In the European Green Deal the goal is set to reduce transport emissions by 90% by 2050 when compared to 1990 levels, to which the aviation sector will also have to contribute [4]. When looking at the emissions of one aircraft, the flight operation phase of the aircraft is responsible for 97% of CO_2 emissions, mainly due to the burning of fuel [5]. A lower weight of an aircraft would lead to lower fuel use during its lifetime, reducing its emissions and fuel cost [6]. This is where composite materials, in the form of a polymer matrix and fibre reinforcement, can play a large role due to their high specific strength and stiffness and aerodynamic shaping possibilities, allowing for the design of lightweight structures [7][8]. Aircraft manufacturers have increasingly been using composite materials within aircraft structures for several decades, and more recently in the Airbus A350 and the Boeing 787 of which the aircraft structure consist of more than 50% by weight out of composites [9], as shown in Figure 1.1.
Within these aircraft, thermoset matrix composites are more frequently used, but interest and research into using thermoplastic matrix composites is growing [10]. This is due to the high processing rates, favourable storage conditions, improved chemical resistance and toughness and recycling opportunities of thermoplastic materials compared to thermoset materials [11] [12]. From the global use of carbon fibre composites, it is estimated that thermoplastic composite make up around 30% by revenue [13].

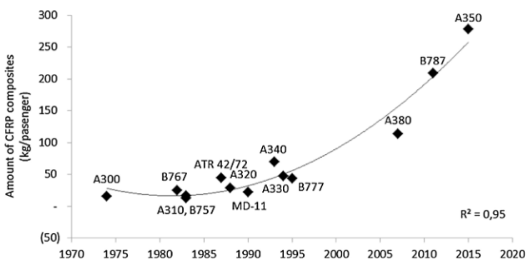


Figure 1.1: Amount of composite material used per passenger in the manufacturing of aircraft over the last decades [14]

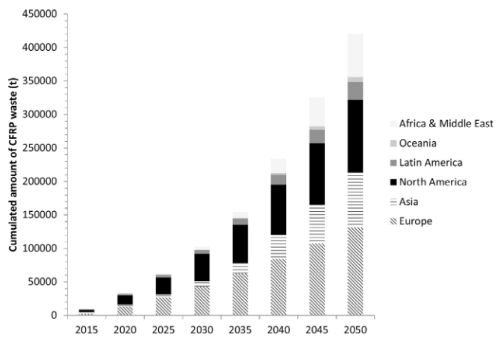


Figure 1.2: Global accumulated composite waste from the commercial aeronautics sector divided per region[14]

With the use of composite materials increasing, the amount of waste generated will also increase - first as production waste and later as end-of-life waste. It is estimated that by 2050, a total amount of roughly 450 ktons of carbon fibre composite waste will be generated, as shown in Figure 1.2. Out of this total amount of composite waste, 30% is estimated to come from production processes. which is in line with other findings [15][16]. The term Buy-To-Fly ratio is used in the aerospace industry to indicate the ratio between the part weight and the production waste weight. For thermoplastic composite materials this ratio varies from 1.05-2.0 depending on the process used [17].

The production of thermoplastic composite parts for the aerospace industry has evolved from very simple hand operated shaping processes in the early 1990's, to fully automated complex part production currently [18]. During the production not all material that starts the process ends up in the final part, due to blank cutting and trimming operations, and is generally called production waste. This material can contain defects such as fibre wrinkling, misalignment of the fibres and can be contaminated with coatings, films and other types of contaminants.

Labelling excess material from production as waste is thinking within a linear economy along the "take-make-waste" principles. As the limits of a linear economy are becoming more visible - a steep growth in raw material demand, dependency on other countries for critical materials and depletion of natural capital coupled with increasing emissions - a transition is required to a circular economy. A goal which the dutch government wants to achieve by 2050 [19] [20]. Within a circular economy the focus is on eliminating waste. Waste flows do not exist within a circular economy, these are seen as resources which can be re-used in the production process [21]. In such a system, no external supply of raw materials would be required anymore, and all materials are circulated endlessly. The difference between a linear economy, an economy with feedback loops and a circular economy is presented in Figure 1.3. Within this project, the 'waste' material from the thermoplastic composite production process will not be referred to as waste, but as a co-product. A co-product can be defined as: *"any of two or more products coming from the same unit process or product system"* [22]. This implies that the material is not waste but a valuable product resulting from the production process, which can be repurposed or used as a resource in subsequent processing steps.

The circular economy has three principles driven by design: eliminate waste and pollution, circulate

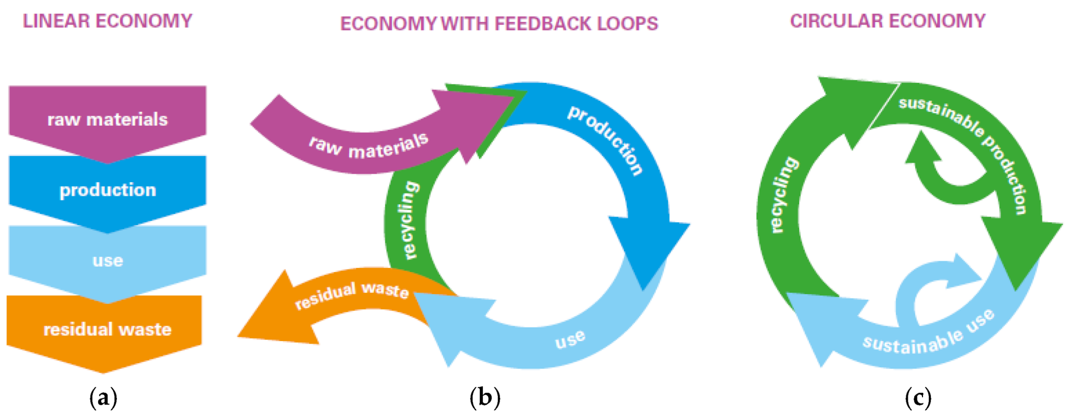


Figure 1.3: Illustration of a (a) linear economy, (b) economy with feedback loops and (c) circular economy [21]

products and materials at their highest value and regenerate nature [23]. The methods that allow for the circulation of materials and the regeneration of materials can be summarised in the form of a butterfly diagram, as shown in Figure 1.4. The right side is focused on the technological cycle of materials and products, where the aim is to circulate the materials and products through repair-re-use remanufacturing and recycling, with a decreasing order of preference [24].

Composite materials are notoriously hard to recycle as they consist of multiple components, which are not easy to separate to bring them back to their raw materials [25]. Current efforts focus on the recovery of the carbon fibres from the material through mechanical or thermal recycling, as these are the most valuable constituent[26]. Other methods that also incorporate the matrix material, focused on transforming this heterogeneous supply of material into a homogeneous material through size reduction and mixing. In this process the fibres are cut into smaller dimensions, sacrificing mechanical properties for improved processing possibilities, and processes using injection- or compression moulding into non-structural applications such as hatches, panels and hinges [17] [27]. This is considered a form of downcycling, where the processing results in a loss of function and value of the material, resulting in a lower grade product in the end [28][29]. As such, closer material circulation loops should be considered, such as reuse, to capture and retain the value of the material.

Re-using the thermoplastic composite co-products as-is can be done through repurposing, resizing,

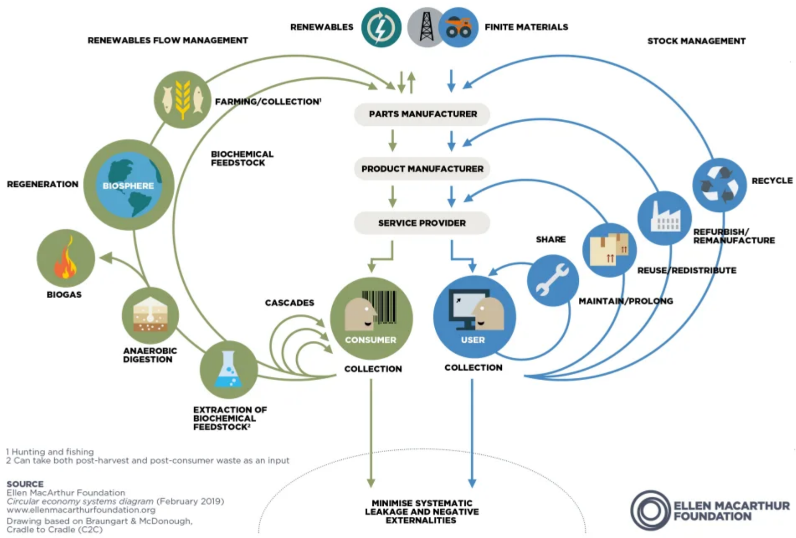


Figure 1.4: Butterfly figure detailing the biological cycle (left) and the technological cycle (right) of products and materials within the circular economy [24]

or reshaping the material, so called structural reuse [30]. Reshaping of thermoplastic based composites is possible, as their processing is purely physical and reversible [31]. This would allow for the processing of thermoplastic composite production co-products into new forms with little energy input, whilst retaining the integrity of the material. Furthermore, it would provide value for applications where high-performance materials are valued (allowing for weight savings or better performance), but have been omitted due to their high cost [32]. However, this has not been demonstrated for production co-products up to this date, and initial explorations of end-of-life thermoplastic composite material have been limited to lower grade applications [33].
Using thermoplastic composite production co-products in a design process also comes with its limitations, including the variety in the geometry, the constituents and the supply. As such, using these materials in a design process is not a trivial task, and there are little guidelines for designers and engineers that can help them during the process.

1.2. Project aim

This project aims to explore how designers and engineers can design new applications from aerospace thermoplastic composite production waste material. To guide this process one main research question is established, with several sub-questions:

> How can designers and engineers design new applications from thermoplastic composite production waste?

With the sub-questions:

1. What is thermoplastic composite production waste?
    (a) Which thermoplastic composite materials are commonly used in Aerospace applications?
    (b) What are the main types of production waste from the aerospace industry?
    (c) What are the characteristics of this waste material?
    (d) How are the properties of the waste material affected by its characteristics?
2. How can thermoplastic composite production waste be shaped into new forms?
    (a) What are possible options for reshaping thermoplastic composite materials?
    (b) How can a suitable processing method be selected for the waste material?
    (c) What are the underlying physical mechanisms for reshaping?
    (d) How do these underlying physical mechanisms affect the shaping limitations?

(e) What are suitable processing parameters for the waste material?
(f) What methods and equipment is currently used in industry and literature for shaping thermoplastic composites?

3. How is the design process affected when using a waste composite material?

    (a) What aspects of the material are important to consider?
    (b) how do these aspects influence the design process?

1.3. Method

To answer these questions a design process is utilised, which can be characterised with four phases: Discover, Define, Develop and Deliver. The boundary between the phases is not fixed, and in some cases iteration was necessary between the phases. This is reflected in the diagram shown in Figure 1.5. A further detailed version of this figure ca be found in Appendix A

During the discover phase, thermoplastic production waste from the aerospace industry and the shaping of thermoplastic composite materials are explored. In Chapter 2, the thermoplastic composite materials and their production methods are further detailed, and a selection is made for a production co-product for use in the rest of the project. Chapter 3 is centred on the shaping of thermoplastic composite materials, and a new structural form of the production co-product is created through a short ideation process. Further information on the processing of the material in the chosen form is also established. In Chapter 4 a framework is presented for the rest of the thesis report, creating two branches of the report focusing on the engineering dimension, and the design dimension of a product made from thermoplastic production co-products. For the design dimension a design vision is created to guide the design process. The engineering dimension is described in Chapter 5 , starting with exploring possible applications of the form of the production co-product. From this exploration an intermediate structural form is selected, followed with an analytical model of the form that can be used in a design process. The chapter concludes with an exploration of the design freedom with examples of applications. In Chapter 6 the design dimension of the form is explored, starting with an ideation process that follows the design vision. From this ideation process a single idea is selected for further concept development, detailing the shape and form, proportions and scale, user interaction and ergonomics and the materials and materialisation. An evaluation of the results obtained from both the design and engineering dimension is presented in Chapter 7, discussing whether the designs meet their intended goal, and any limitations of the designs. The project is concluded in Chapter 8, answering the research question, discussion any limitations of the entire project and making recommendations for future work. A personal reflection on the learning goals defined at the start of the project and the process followed is presented in Chapter 9, which concludes the content of this thesis report.

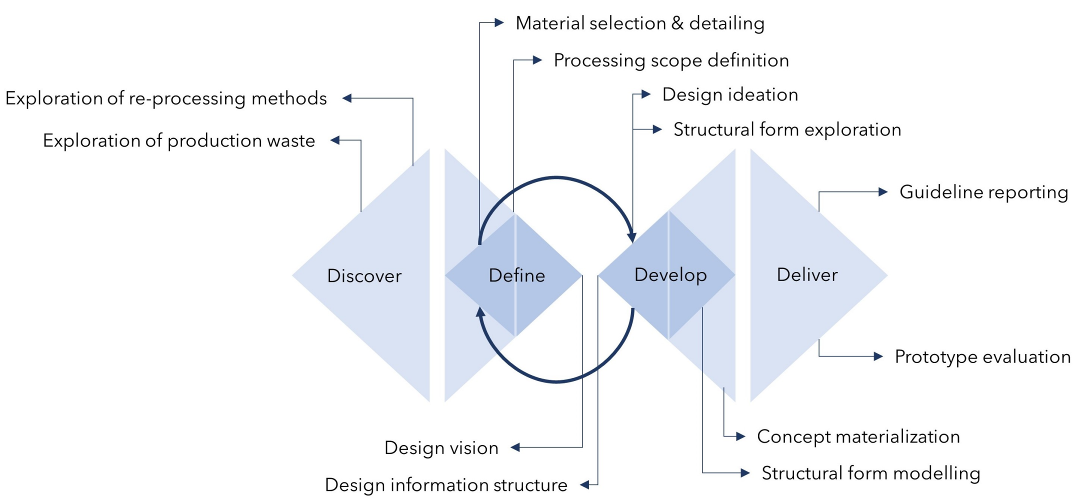


Figure 1.5: Double diamond approach followed during the project, with activities per phase

2
Exploration of thermoplastic composite production waste

2.1. Introduction

In this chapter the use of thermoplastic composite materials, the production and waste generated from these production processes within the aerospace industry is explored. Firstly, an introduction of thermoplastic composite materials is given, which is followed with a detailing of the thermoplastic composite materials used within the Aerospace Industry. The next section describes the production processes currently used for thermoplastic composite parts for use in aerospace applications, with some examples. The last section explores the production waste that is generated from these production processes, groups the various types of waste in 5 types and describes these in more detail.

2.2. Thermoplastic composite materials used in Aerospace

This section provides background information on the constituents of thermoplastic composite materials, and how these are integrated into aircraft structures. This starts with a definition of composite materials and is followed with a description of fibre reinforcements and thermoplastic matrices used in the aerospace industry. With the constituents defined, three types of composite material structures and their applications are explored: continuous fibre reinforced composites, short fibre composites and sandwich-style composites.

A composite material can be defined as a material that consists of more than one constituent. Generally these are two materials with dissimilar properties, that are combined to achieve a balance in performance that cannot be achieved by the materials separately [34]. This would include for instance materials like concrete, wood and brick, but the discussion in this chapter is limited to two constituents: fibre materials and thermoplastic resins.

Combining fibre materials together with a thermoplastic resin can result in a variety of different composite materials. In Figure 2.1 three different combinations of fibres and thermoplastic matrix are shown.

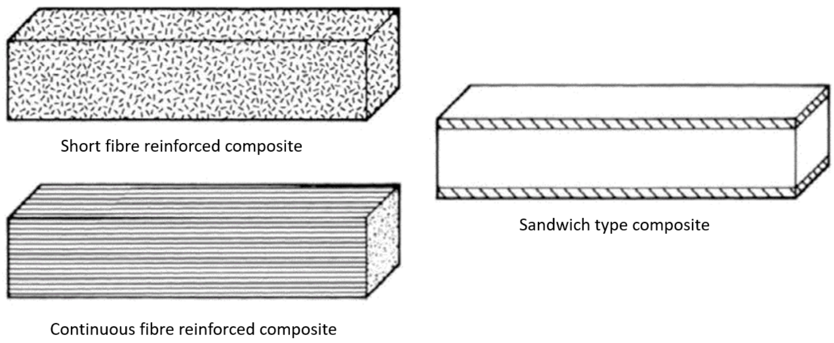


Figure 2.1: Three different composite material types from fibre materials and thermoplastic resins. Adapted from:[34]

2.2.1. Fibre reinforcement

Fibres are considered the primary load-carrying constituent within a composite material, primarily in the longitudinal direction of the fibre. The mechanical and thermal properties of a fibre depend on the fibre type, the fibre volume fraction v_f, the fibre length, the fibre orientation and the arrangement within the composite. The most commonly used fibres within aerospace structures are glass, aramid and carbon fibres, and are used to increase structural performance and reduce weight, vibration and corrosion [35].

The diameter of the fibres themselves varies from 5 μm to 15 μm, where carbon fibres are generally smaller, and glass fibres larger. In Figure 2.2, a tensile fracture surface of a composite material is shown, demonstrating the size of the fibres within a composite material.

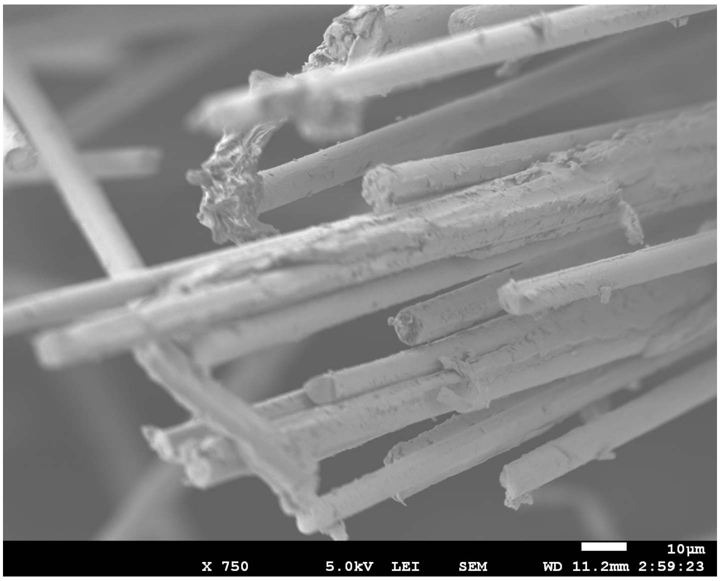


Figure 2.2: Scanning Electron Microscopy image of a tensile fracture surface of a glass fibre-Polyphenylene sulfide (PPS) composite material

In general,the fibres are supplied in a strand (for glass fibres) or tow (for carbon & aramid fibres), where a large amount of fibres are bundles together. A common tow size is in the range of 1,000-3,000, 1K or 3K, but can be as high as 50,000, 50K [12]. These tows or strands can be organised in uni-directional patterns, or in a two dimensional fibre patterns.

For the unidirectional patterns, the fibres are all aligned in a single direction. As a result, high performance in the longitudinal direction of the fibre is obtained, but the properties in the transverse direction are dependent on the matrix material, and as such lower. To improve the transverse properties a two dimensional fibre patterns can be used, such as a woven pattern. In a woven pattern the two directions are referred to as warp (lengthwise) and weft/fill (crosswise), and the type of fibres used, the tow size and the pattern dictate the properties of the fabric. In Figure 2.3, all four fibre alignment patterns are summarised.
The type of weave also has an effect on the properties and behaviour of the material. With a tightly woven weave such as the plain weave, there is little movement of the fibres possible, and as such reduces the drapeability of the material. Furthermore, the mechanical properties of the material are reduced, as the fibre has to cross over other fibres more relative to the other fabrics. This up and down motion of the fibre in the weave pattern is called crimp. Crimp not only has an effect on the mechanical properties, but also on the processing characteristics of the material. With increasing crimp, the permeability of the material is increased, and as such resin flow is enhanced.

In Table 2.1, a summary of the properties of different fibre types is given. It is clear that Carbon fibres in general have a very low strain to failure, less than 1%, and as such care has to be taken during processing not to break these fibres. Depending on the application, a higher modulus fibre with a lower

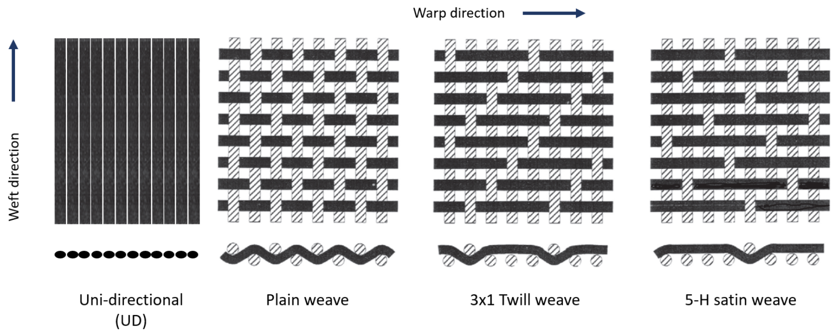


Figure 2.3: Uni-directional, Plain weave, 3 x 1 Twill weave and 5-H satin weave patterns

tensile strength can be selected, or a fibre with a higher tensile strain to failure, if this is preferred.

Within the aerospace industry, carbon fibres are preferred in structural applications where a high strength and stiffness is required, at the lowest weight possible. Glass fibres are used in structural applications instead of carbon fibres whenever they can, when stiffness is not a priority, due to their lower cost and still relatively high specific strength and toughness. They are also commonly used for structures where transparency to electromagnetic radiation is required, such as radomes. Common fibre types include E-glass fibers, which are electrically (E) insulating and can also be used as a barrier layer for preventing galvanic corrosion in carbon fibre based composites, and S-glass fibres which contain more silica (S) and can withstand higher temperatures [36]. Aramid fibres are used in applications where the structure should have a impact resistance and acoustic emissions need to be reduced at a low weight, such as the engine covers of an aircraft[37][38].

Table 2.1: Summary of the properties of the three main fibre types used: Glass, Carbon & Aramid. (PAN and pitch denote a difference in precursor used in carbon fibre production) Adapted from [12][39]

	Filament diameter [μ m]	Density [g/cm^3]	Tensile Modulus [GPa]	Tensile Strength [MPa]	Strain at failure [%]	Cost ($ US/kg)
E-Glass	10	2.54	72.4	3450	4.8	1.55-2.65
S-Glass	10	2.49	86.9	4300	5	-
T300 (PAN carbon)	7	1.76	230	3650	1.5	40-80
AS-4 (PAN carbon)	7.1	1.79	231	4410	1.7	40-80
IM-7 (PAN carbon)	5.2	1.78	276	5516	1.9	60-130
IM-55J (PAN carbon)	-	1.91	540	4020	0.8	220-275
P120 (pitch carbon)	-	2.16	823	2200	0.3	1750-2650
Kevlar 49 (aramid)	11.9	1.45	131	3620	2.8	35-100

2.2.2. Thermoplastic matrix

The function of the matrix material within a composite material is to transfer the load among the fibres, and protect them from the environment. Generally two types of matrix materials can be used: thermoset or thermoplastic polymers. Using thermoplastic polymers in composite structures within the aerospace industry has been explored since the 1990's, when the limitations of thermoset polymers became apparent in terms of chemical resistance, mechanical performance (failure strains, energy absorption and toughness) and manufacturing (processing time, assembly and reprocessing) [31][12]. Thermoplastic matrix materials are in general more tough than thermoset matrix materials, they offer better resistance against chemicals found in aircraft structures, and they allow for rapid manufacturing. Currently, thermoplastic matrix material are increasingly being used in primary and secondary aircraft structures, starting from rib structures, to fully integrated skin-stiffened panels [40][11].

Thermoplastic matrix materials consist of long chain molecules that are entangled with each other. There is no permanent chemical bonding between these chain molecules, so called cross-links, unlike with thermoset polymers. This lack of chemical bonds between the molecular chains makes the processing of thermoplastic reversible.

The entanglement of the molecular chains can be random, which is the case in amorphous thermoplastic polymers, or semi-arranged which is the case for semi-crystalline thermoplastic polymers. In Figure 2.4 the chain molecule entanglement for an amorphous and semi-crystalline polymer is illustrated. The properties of semi-crystalline polymers are dependent on the percentage of crystallinity within the material, where a higher percentage of crystallinity indicates higher mechanical properties [12].

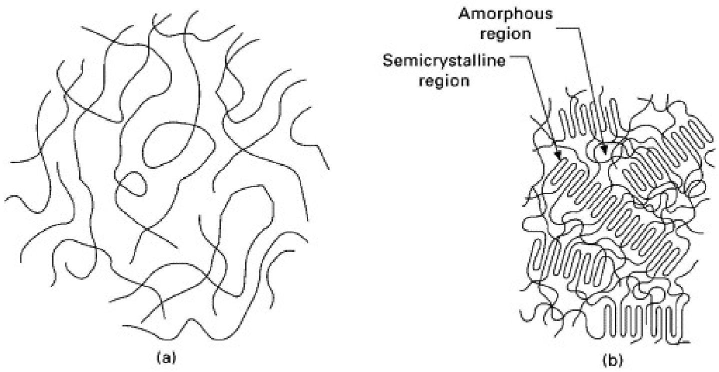


Figure 2.4: Illustration of the amorphous (a) and semi-crystalline structure (b) within a thermoplastic polymer [37]

Other factors that control the mechanical properties of thermoplastic polymers are the degree of polymerisation which affects the chain molecule length and the presence and size of side groups of these chain molecules [37]. The mechanical properties of a thermoplastic material are important for the use in composite structures, as matrix can distribute the tensile load over multiple fibres, and under compression the matrix material can support the fibres to prevent them from buckling [31]. As such, the most important properties of a thermoplastic to be used in structural applications are its elastic modulus, tensile strength and shear strength.

The two main two groups of thermoplastic polymers can be separated into three categories, standard, engineering and high-performance polymers, as shown in Figure 2.5. High-performance thermoplastics are used in applications that demand high-structural performance in high-temperature environments, such as in the aerospace or automotive industry. Out of these, PEEK, PEKK, PPS and PEI are most commonly used in composite structures for aircraft [37] [41].

The processing of thermoplastic matrix materials is mainly dependent on the temperature. When thermoplastic polymers are heated they change from a hard glassy solid to a soft rubber above the glass transition temperature T_g. In this state their mechanical properties are lower, but this effect varies between amorphous and semi-crystalline polymers When the temperature is increased further, the polymer changes from a rubbery solid to a liquid above the melting temperature T_m. For amorphous polymers this distinct melting temperature is not present, as the crystalline parts of the polymer are melting at this temperature, and the polymer turns to a melt above the glass transition temperature T_g. In Figure 2.6 the elastic modulus of amorphous and semi-crystalline polymers is shown for different temperatures, demonstrating the different phases for amorphous and semi-crystalline polymers.

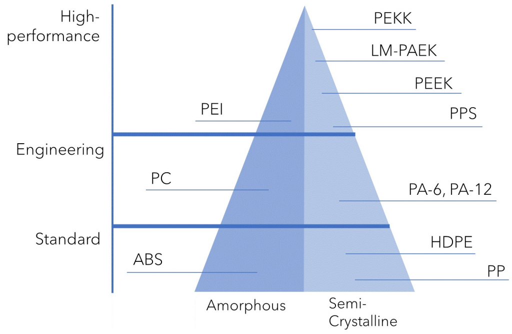


Figure 2.5: Overview of the commonly used thermoplastics within the aerospace industry based on their chemistry and performance [42][43]

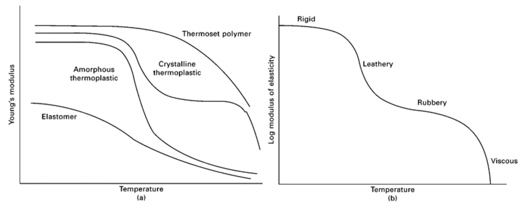


Figure 2.6: Change in the Young's modulus (a) and polymer state (b) with increasing temperature [44]

Upon cooling, both amorphous and semi-crystalline polymers will return to their original state, where for semi-crystalline polymers the cooling rate affects the degree of crystallinity and the size of the crystalline regions, as shown in Figure 2.4, in the solid state of the material [12].

In primary and secondary aircraft structures PEEK, PEKK and PPS are used, where the latter is used in structures with a lower service temperature such as wing leading edges [41][45]. PEI is used in applications that demand high-toughness, and high fire, smoke and toxicity performance such as aircraft interior structures [46][41]. In Table 2.2 and Table 2.3 the mechanical properties and phase change temperatures are summarised respectively.

Table 2.2: Summary of the mechanical properties of the four most commonly used thermoplastic resins used in composite structures in aircraft. Data taken from [12][47]

	Density [g/cm^3]	Tensile Modulus [GPa]	Tensile Strength [MPa]	Shear Strength [MPa]	Strain at failure [%]
PEEK	1.30	3.7	110	53	25
PEKK	1.30	3.45-4.40	90-115	138	12
PPS	1.35	3.45	93	-	15
PEI	1.28	3.45	117	-	60

Table 2.3: Summary of the thermal properties of the four most commonly used thermoplastic resins used in composite structures in aircraft. Data taken from [46]

	Molecular structure	Glass transition temperature T_g [° C]	Melting temperature T_m [° C]	Processing temperature T_p [° C]
PEEK	semi-crystalline	140	343	370-400
PEKK	semi-crystalline	160	337	370-400
PPS	semi-crystalline	90	280	300-330
PEI	amorphous	218	220	320-350

2.2.3. Continuous fibre reinforced composites

Continuous fibre reinforced composites consist of fibre reinforcement that is continuous throughout the structure. In Figure 2.7 the constituents of a continuous fibre composite material are illustrated.

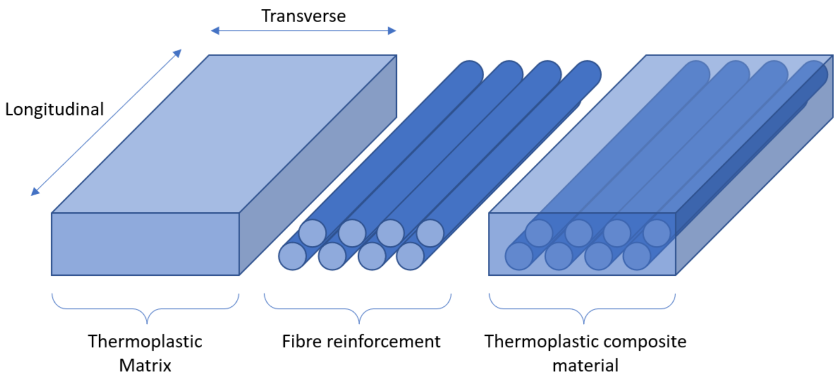


Figure 2.7: Constituents of a continuous thermoplastic composite material

One of the key parts of a composite structure consisting of a fibre reinforcement and a thermoplastic composite matrix, is the fibre-matrix interface. The fibre-matrix interface governs the load transfer between the two different materials, and governs its performance. The fibres within the material have a very large surface area-volume ratio, which means that there is enough area for bonding and load transfer. For a good bond, the fibres have to be covered fully by the resin, and both mechanical and chemical bonding has to be present [12]. During the processing the wetting of the resin is controlled through the application of heat, and mechanical locking of the fibres is created due to the difference in thermal expansion/contraction. For the chemical bonding, surface treatments, *sizings*, can be applied to the fibres that improve bonding. In the case of insufficient bonding debonding can occur during loading, leading to a loss of load transfer and exposure of the fibre to the environment.

The fibre volume fraction v_f is commonly used for the determination of the stiffness and strength of the continuous fibre composite material on a meso-scale. To determine this fraction, Equation 2.1 can be used, where ρ_f and ρ_m are the density of the fibre and matrix, and w_f w_m are the fibre and matrix weight fractions respectively.

$$v_\mathrm{f} = \frac{\frac{w_\mathrm{f}}{\rho_\mathrm{f}}}{\frac{w_\mathrm{f}}{\rho_\mathrm{f}} + \frac{w_\mathrm{m}}{\rho_\mathrm{m}}} = \frac{\rho_\mathrm{m} w_\mathrm{f}}{\rho_\mathrm{m} w_\mathrm{f} + \rho_\mathrm{f} w_\mathrm{m}} \tag{2.1}$$

Where w_f can be determined by dividing the weight of the fibres in a composite material by the total weight of the composite material, as shown in Equation 2.2, .

$$w_f = \frac{W_f}{W_c} \tag{2.2}$$

with W_f as the total fibre weight, and W_c as the total composite weight. Note that W_m = W_C - W_f, and $w_m = 1 - w_f$.

Using this fibre volume fraction the elastic modulus and the strength can be determined in the longitudinal direction through the rule of mixtures, as demonstrated in Equation 2.3 and Equation 2.4.

$$E_\mathrm{L} = E_\mathrm{f} v_\mathrm{f} + E_\mathrm{m} v_\mathrm{m} \tag{2.3}$$

$$S_\mathrm{L} = S_\mathrm{f} v_\mathrm{f} + S_\mathrm{m} v_\mathrm{m} \tag{2.4}$$

Where E_L denotes the elastic modulus of the material in longitudinal direction, and S_L denotes the strength of the material in longitudinal direction. In the transverse direction, the matrix plays larger role, as the fibres are not oriented perpendicular to the load, and the elastic modulus can be estimated by using Equation 2.5.

$$E_\mathrm{T} = \frac{E_\mathrm{m} E_\mathrm{f}}{E_\mathrm{f}(1 - v_\mathrm{f}) + E_\mathrm{m} v_\mathrm{f}} \equiv \frac{E_\mathrm{m}}{1 - v_\mathrm{f}} \tag{2.5}$$

it is apparent that with a high fibre volume fraction, high mechanical properties can be obtained. The theoretical maximum fibre volume fraction in an hexagonal array is 91%, but due to processing constraints and the occurrence of defects at very high fibre volume fractions most high-performance composites are between 0.5 and 0.65 [12].

In most applications, the meso-scale composite structures are stacked in laminate form, creating a composite material at a macro scale [12]. This stacking is illustrated in Figure 2.8.

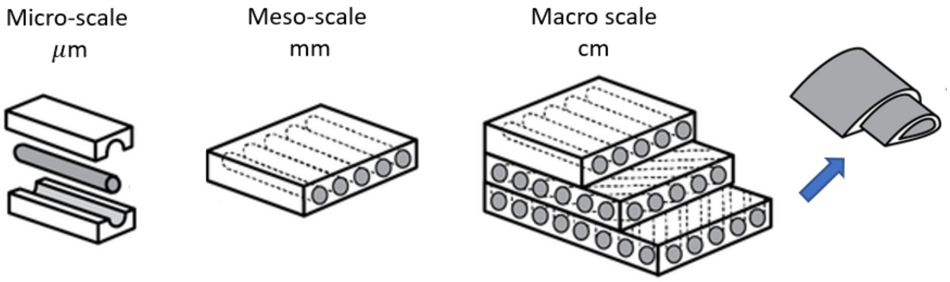


Figure 2.8: Transition from micro to macro level for composite materials (and their application). Adapted from:[48]

The stacking of the layers of composite plies is done in a defined order, the layup, which affects the macro scale properties of the material and can be tailored to the application. This layup describes the orientation of each respective ply with respect to a common axis. On a ply level, one direction described the longitudinal direction of the fibres, the 1-direction, and one orientation transverse to the direction of the fibres, the 2-direction. On a ply level, the leading orientation is always longitudinal to the fibres, the 1-direction. For a woven fabric is the weft direction as shown in Figure 2.3. Two examples of layups are shown in Figure 2.9 and Figure 2.10, where one is an orthogonal layup, only featuring plies that are oriented at 90° with respect to each other, and a quasi-isotropic laminate (QI), where the difference is only 45°. Compared to a unidirectional layup, the modulus of the orthotropic layup is lower in the 0° direction, by a fraction $\frac{4}{6}$, but it offers a higher modulus in the transverse 90° direction due to the presence of aligned fibres. For a QI layup, the modulus is constant in all 4 directions (0°, 90°, 45° and -45°), but it is roughly one third of the modulus of a unidirectional composite in the fibre direction. These layups are used in applications where in-plane isotropic behaviour is required and/or when the loading on the structure is variable in directions over time. Within aerospace applications, the two most common layups used are the cross ply [0/90] and Quasi-Isotropic [0/$\pm$45,90], where the cross-ply is used when the shear loads are absent [35].

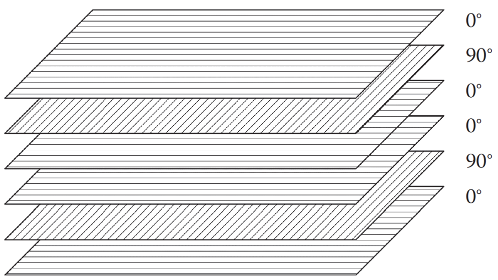


Figure 2.9: Orthotropic laminate layup: [0/90/0]$_S$ [12]

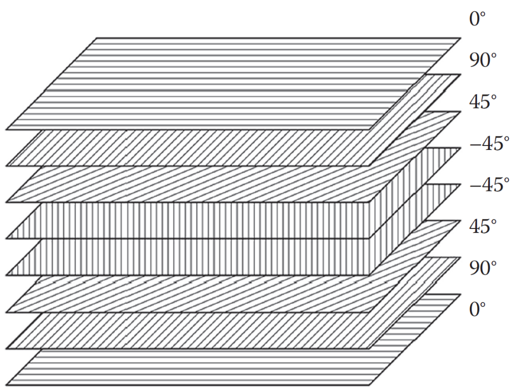


Figure 2.10: Quasi-Isotropic laminate layup: [0/90/45/-45]$_S$ [12]

One example of an application of a continuous fibre structure in aerospace applications include the J-nose of the airbus A380, manufactured using woven glass fibre as fibre reinforcement and PPS as a matrix material [35]. Another is the vertical of the Gulfstream G650, using woven carbon fibre as the reinforcement, and PPS as the matrix [40]. These two examples are illustrated in Figure 2.11 and Figure 2.12.

Figure 2.11: J-Nose of the Airbus A380 made from woven glass fibre/PPS composite material by GKN Aerospace [49]

Figure 2.12: Vertical stabiliser of the G650 aircraft made from woven carbon/PPS composite by GKN Aerospace [41]

2.2.4. Short fibre reinforced composites

Short fibre reinforced composites consist of thermoplastic matrix material and short length fibre reinforcement, making up about 20-40% of the material by volume [12][34]. These fibre lengths range from 10mm to 25mm, where longer fibre lengths can increase the properties of the material, but reduces the processability [17]. A Scanning Electron Microscopy (SEM) image of a short fibre reinforced composite surface is shown in Figure 2.13, where the random direction and the short length of the fibres is clearly visible.

Figure 2.13: SEM image of the polished surface of a short fibre composite material [50]

The addition of the short length fibres to a thermoplastic resin increases its tensile strength, stiffness, impact strength, fatigue strength, creep resistance, property retention at elevated temperature and dimensional stability, when compared to the neat resin [34]. With higher fibre volume fractions, these properties increase.

Other important factors that affect the mechanical properties of short fibre composites are the type of fibres used, their length and their aspect ratio[51]. If a short fibre composite material is loaded in tension, the matrix material experiences shear stress whilst the fibres are loaded in tension. The preferred failure mode of short fibre reinforced composites is tensile fibre failure, as their strength is higher than the shear strength of the matrix material. Increasing the length and diameter of the fibres increases the contact area between the fibres and the matrix, decreasing the shear stress under loading. If this length is too small, the composite material can fail in shear either in the fibre-matrix interface or the matrix material itself, which is much lower than the preferred fibre tensile failure mode. When assuming that the fibres are perfectly parallel, a relation for the critical fibre length can be determined, which describes the fibre length necessary for fibre tensile failure. This relation is given in Equation 2.6, where S_f is the fibre tensile strength, d_f is the fibre diameter, $S_{i/m}$ is the shear strength of the interface or matrix, and l_c is the critical fibre length [12].

$$l_\text{c} = \frac{S_\text{f} d_\text{f}}{2S_\text{i}} \tag{2.6}$$

In general, the fibre length used for effective reinforcement should be at least 10 times larger than the critical fibre length, due to the random orientation of the fibres. For unidirectional short fibre composites, with a fibre length larger than the critical fibre length the tensile strength can be calculated using Equation 2.7.

$$S_{\text{L}t} \cong S_\text{f}\left(1 - \frac{l_\text{c}}{2l_\text{f}}\right) v_\text{f} \tag{2.7}$$

Where $S_{\text{L}t}$ is the tensile strength in longitudinal direction, l_f is the fibre length, and v_f is the fibre volume fraction. To achieve more than 90% of the tensile strength of continuous fibre composites, the fibre length has to be at least 5 times the critical fibre length, assuming that the orientation of each fibre is exactly in line with the load, and parallel to another fibre [12].

A current application of a short fibre reinforced composite structures in aerospace is the door hinge of the Airbus A350 XWB, utilizing PEEK as a resin with 40% carbon fibre reinforcement [52]. Another example that has been designed and testing according to flight requirements, is a rotorcraft access panel from recycled carbon fibre/PPS granulates. The granulates are made from carbon fibre/PPS QI laminate trimmings, with a fibre volume fraction of 20 % and fibre length of 15-20mm [53]. These examples are illustrated in Figure 2.14 and Figure 2.15.

Figure 2.14: Door hinge for the Airbus A350 XWB made from PEEK/CF 40% reinforcement made by Airbus Helicopters [52]

Figure 2.15: Rotorcraft access panel made from recycled CF/PPS granulates by T. de Bruijn [53]

2.2.5. Sandwich-type composites

A sandwich type-composite is usually consists of three components: the top and bottom face sheet and a core material. The face sheets consist out of a thin laminate, and the core out of a low-density material such as a foam or honeycomb material. An overview of this is shown in Figure 2.16. The main function of sandwich type composites within aerospace applications is offer high ratios of stiffness and strength to weight, but can also be used for acoustic damping, thermal insulation and increased energy absorption when compared to monolithic (non-sandwich) structures. With the right material for the face sheets and core materials, high ratios of stiffness-weight and strength-to-weight can be obtained.

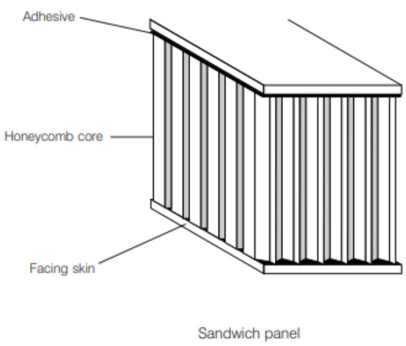


Figure 2.16: Overview of the constituents of a sandwich panel [54]

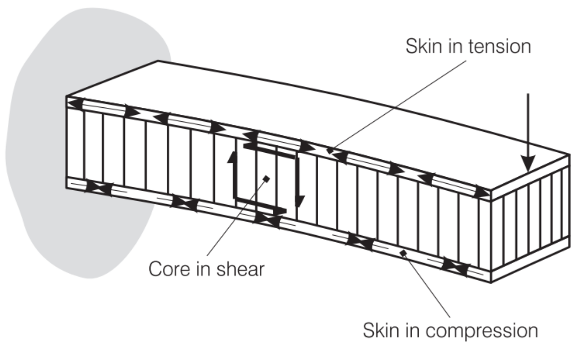
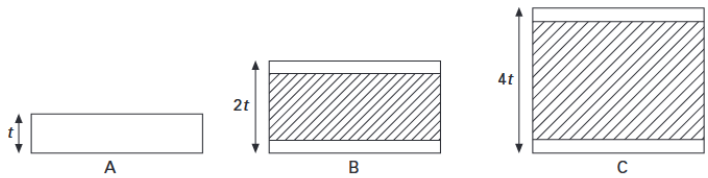


Figure 2.17: Loads present in the face sheets and core material in a sandwich panel under bending [54]

Sandwich composites offer a superior structural efficiency to monolithic panels in bending, as is illustrated in Figure 2.18. By using a lightweight core material that places the stiff and strong face sheets far from the neutral axis, a stiff and strong structure is obtained. The loads present in a sandwich structure under bending are summarised in Figure 2.17. The deflection of the sandwich structure can be separated into two parts, the bending deflection and the shear deflection. The bending deflection



Property	A	B	C
Relative stiffness	100	700	3700
Relative strength	100	350	925
Relative weight	100	103	106

Figure 2.18: Relative stiffness and strength of a monolithic and sandwich composite, demonstrating the structural efficiency of the sandwich panels [35]

is mainly based on the tensile and compressive modulus of the face sheets, and the shear deflection on the shear modulus of the core materials. As such, materials used for the face sheets are generally continuous fibre composites, as these can offer a high specific stiffness and strength. For the core materials, honeycomb materials or foams can be used, which offer a high shear modulus and strength.

In designing a sandwich composite material, the failure modes of both the face sheets and the core material has to be taken into account. In Appendix B these failure modes have been summarised for different loading conditions. For the face sheets and the core material, the tensile, compressive and shear strength are the most important properties for failure. If the face sheets consist of a continuous fibre composite laminate, the layup can be adapted to increase the tensile and compressive strength. For the core material, a optimal match between the material strength properties and the thickness of the core has to be found. The analysis of a sandwich composite material can be done using standard beam equations, and a set of equations that allow for the preliminary analysis of stresses in the face sheets and core material. The analysis of a sandwich composite structure is summarised in Appendix C.

Sandwich composite materials are commonly found in secondary structures, such as control surfaces, radomes, floor-panels and vertical tail-planes. This is demonstrated for the Citation III in Figure 2.19, where a specific application of a thermoplastic composite sandwich panel can be found in the G550 and G650 pressure bulkhead floor panels, as shown in Figure 2.20.

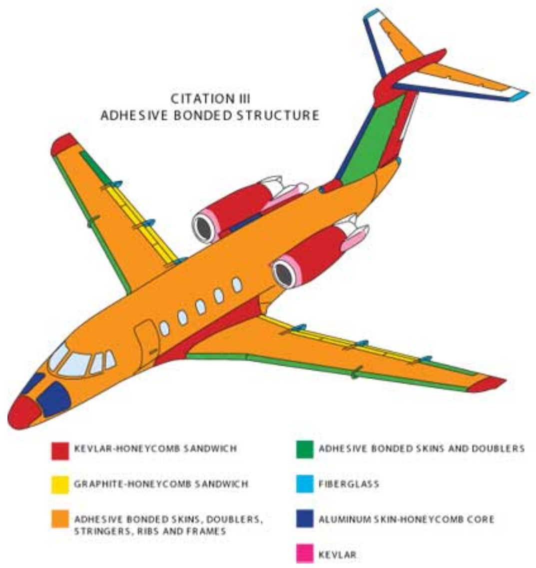


Figure 2.19: Applications of sandwich composite materials in the Citation III aircraft made by Cessna (1982-1992) [55]

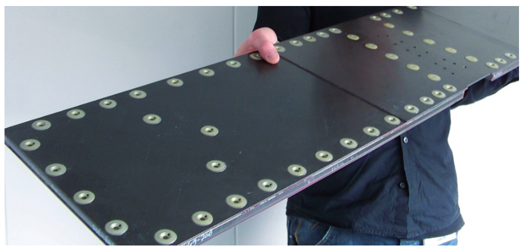


Figure 2.20: Pressure bulkhead floor panel for the G550 and G650 made from carbon fibre/PEI face sheets by GKN Aerospace [41]

2.2.6. Section takeaways

- Composite materials used in the aerospace industry generally consist of a polymer matrix and a fibre reinforcement
- Out of all fibre reinforcements used in the aerospace industry, carbon fibres offer the highest specific strength and stiffness, and are the most expensive. As such, these types of fibres are only used in primary and secondary structures when strength, stiffness and low weight are critical.
- The fibres used in a composite materials are in the form of bundles, consisting of 1,000-50,000 fibres, which are oriented in a single direction (UD) or woven in different patterns to form a multi-directional weave.
- Thermoplastic composite materials are increasingly being used in primary and secondary structures of aircraft, as they offer increased chemical resistance and mechanical performance, and can be rapidly processed.
- High-performance thermoplastics including PEKK, LM-PAEK, PEEK are commonly used in Aerospace applications as these offer high mechanical properties, good resistance to chemicals and can be used in high-temperatures. Additionally, PEI is used in cases that requires good fire, smoke and toxicity performance and PPS in structures with a lower service temperature.
- Continuous fibre composite structures using a thermoplastic matrix commonly in the aerospace industry use a orthogonal or quasi-isotropic layup, offering reduced mechanical performance for increased isotropy.
- Short fibre composite materials using a thermoplastic matrix offer increased part complexity, at reduced mechanical performance and are used in small but complex parts within the aerospace industry.
- Sandwich type composite structures using a thermoplastic matrix offer superior structural efficiency in bending compared to monolithic structures, and are used in larger panels of the construction of an aircraft that are under bending loads.

2.3. Aerospace thermoplastic composite part production process

In this section the production process of a thermoplastic composite part for the aerospace industry is further explored. The aim is to understand the steps required to make a part, and understand what physical mechanisms are occurring.

The production process of thermoplastic composite materials starts with the impregnation of the fibres with the resin material. One of these processes, melt impregnation will be further discussed in this section. The next step is the stacking of the layers in their specified orientation, and consolidating these to solid material. After pre-consolidating the stack of plies, the material can be shaped using a variety of forming processes, into its final shape. After this step the part is trimmed to its final dimensions, and the material is inspected for any defects. After this, the material can be assembled to other structural parts.

2.3.1. Fibre impregnation

Melt impregnation is one of the methods of impregnating fibres with a thermoplastic resin, to create a composite material. Other methods include solution impregnation, powder coating, film stacking and fibre mixing [12].

In the melt impregnation process, a roll of material is coated on one (or both) sides by a the melted thermoplastic polymer, and subsequently cooled. Using this process a the fibre volume fraction ,v_f, can be tightly controlled, and even specified to a certain side of the fibres. This process is illustrated in Figure 2.21. The function of the air bonding jet in the beginning of the process is to spread the fibres out from each other, to avoid overlaps and expose the fibres fully to the melted polymer. The fibres are

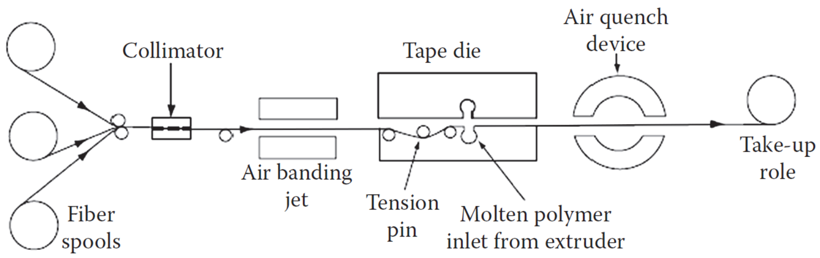


Figure 2.21: Melt impregnation process used to impregnate the fibres with the thermoplastic resin [12]

impregnated through a die that is coated with the molten polymer, which is applied at a high pressure. The air quenching step at the end of the process cools the molten polymer back to its solid phase, to allow it to be spooled up for further processing steps. This process can be used for both semi-crystalline polymers and amorphous polymers, including PEEK, PPS and PEI. Degradation of the polymer can occur if the temperature of the melt is increased above the polymers degradation temperature.

2.3.2. Layup

To form a laminated structure from multiple plies of thermoplastic composite materials, the first step is to stack them according to the specified layup. This is commonly referred to as the layup step of the processing. The layers of thermoplastic composite material can be stacked either by hand, or through automated methods such as Automated Tape Laying (ATL) and Automated Fibre Placement (AFP). During hand-layup the plies are placed by hand onto the tool, and tacked together using a spot welding tool . Such a process was used for the A380 J-Nose structure which is shown in Figure 2.11. Spot welding is used to keep the plies in place during further processing, as the plies are hard and not tacky, allowing them to slip along side each other easily. Hand layup methods can be done with either woven or UD materials, where UD materials require more time to lay-up. To reduce the layup times for UD based composites plies, automated tape laying (ATL) or automated fibre placement (AFP) is used [38]. These automated manufacturing methods have UD tapes on long spools and roll these out along a given path on a flat or curved mould. The width of the tapes determines what kind of method is used, where wider tapes (15-500mm) are used within ATL, and thinner tapes are used within AFP. The choice

Figure 2.22: Layup process of the J-nose of the Airbus A380, using an ultrasonic spot welding tool [41]

depends on the type of mould that is used, where ATL is only suitable for flat moulds and AFP can also be used for curved moulds. The main mechanisms are similar for ATL and AFP, where the to be placed strip of thermoplastic composite material is heated, the 'head' of the tool is moved forward - unrolling the tape whilst subsequently pressing it into the previous layer. During pressing the material is cooled, and forms a solid material together with the layers below. The mechanism for ATL/AFP is illustrated in Figure 2.23, and an example of AFP in practice is shown in Figure 2.24.

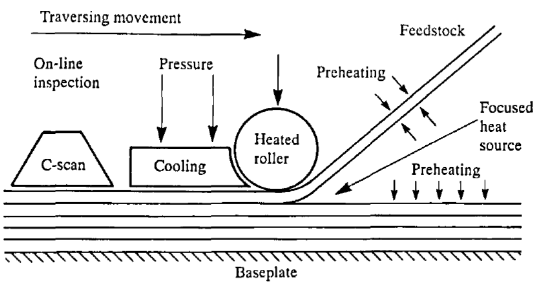


Figure 2.23: Mechanism of automated fibre placement [31]

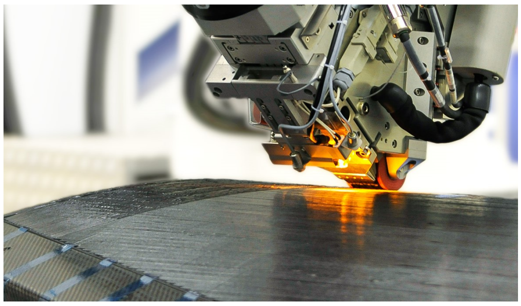


Figure 2.24: Automated fibre placement process used by NLR [56]

2.3.3. Consolidation

When all plies have been stacked in the correct order, they are consolidated together into a single laminate, which is called the consolidation step of the processing. During consolidation the most important processing parameters are temperature, pressure and time. High temperature is required to bring the thermoplastic matrix to a melt with a lower viscosity. In combination with a high pressure, this will ensure that the thermoplastic matrix can flow throughout the plies, wetting out the fibres and removing air from the fibre bundles in the process. On a ply level, the boundaries of the thermoplastic layers are becoming diffuse, due to the molecular diffusion across their interface. This process is called autohesion, and demonstrated in Figure 2.25. This self-adhesion of the layer is helped by the high temperature and pressure, as this creates intimate contact, but can also result in squeeze-out of the resin at too high pressures. It is important to allow enough time for this to occur at the processing temperature, otherwise defects such as voids can be present in the final laminate [12]. An autoclave or heated press can be used to apply the temperature and pressure to the laminate, where the latter is illustrated in Figure 2.26. After a set amount of time has passed under high temperature and pressure, the laminate has to be cooled back to room temperature, turning the polymer from a liquid state back to a solid state. During this process, the cooling rate is controlled, as this can have an effect on the degree of crystallinity, which affects the mechanical properties [12] . The effect of the cooling rate on the degree of crystallinity for a carbon fibre/PEEK composite is shown in Figure 2.27. The pressure is maintained until after the laminate is below the glass transition temperature T_g, to suppress the shrinkage of the material and control its dimensions. This will build up residual stresses inside the material due to the different cooling rates of the fibres and the matrix material, and the temperature gradient between the surface and centre of the laminate. As the material cools outside the mould further this can result in an uneven stress distribution inside the material and lead to warping, causing spring-in of the part. This effect is demonstrated in Figure 2.28.

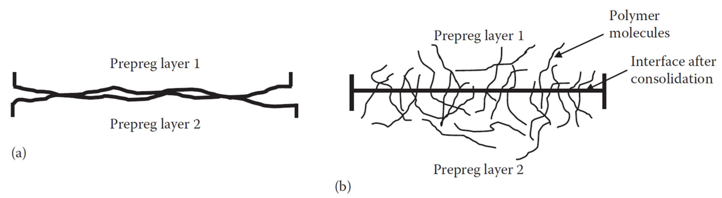


Figure 2.25: Ply to ply interaction during consolidation [12]

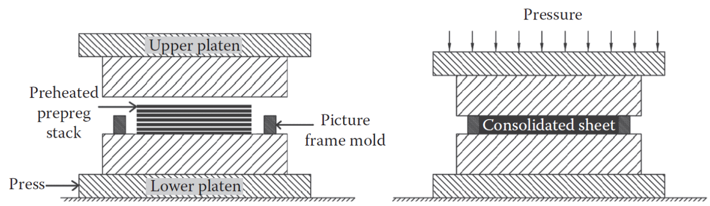


Figure 2.26: Press consolidation of a thermoplastic composite laminate [12]

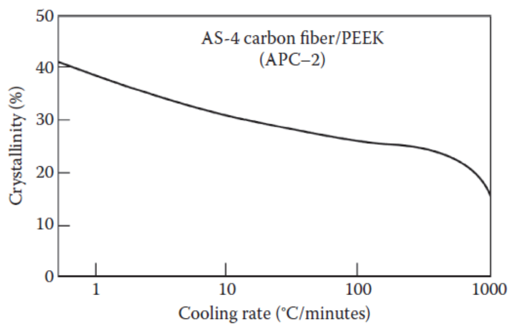


Figure 2.27: Effect of the cooling rate on the degree of crystallinity of a carbon fibre/PEEK composite material [12]

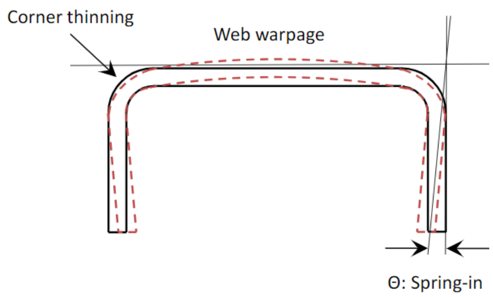


Figure 2.28: Shrinkage of a C-channel shaped part upon cooling [57]

2.3.4. Shape Forming

There are several methods to shape flat sheets into complex forms, including double diaphragm forming, stamp forming and compression moulding[12][31]. Out of these three, stamp forming is currently used for the production of parts for the Aerospace Industry, and is considered the most appropriate for high-rate economical part manufacturing [58][45][59].

Creating a shaped part from a flat sheet can be done in three different ways: Near-net shape forming of a single part, multi-part sheet forming and single part forming. Near net-shape forming starts from a blank cut from a larger sheet, where its dimensions are near the dimensions of the final formed part. After forming, this blank only needs a small amount of trimming around its perimeter to bring it to its final dimensions. Such a blank is shown in Figure 2.29. Multi-part sheet forming includes forming the entire sheet, and then cutting the final parts out of the sheet. An example of this is shown in Figure 2.30. Single part forming includes a blank with excess material around its perimeter, which is used for blank holding, and forming this to the final dimensions. This part will need trimming all around its perimeter to take away the excess blank holding edge to obtain the final part dimensions.

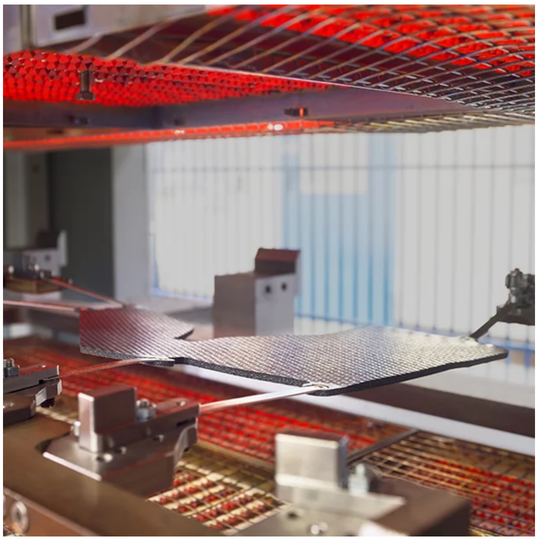


Figure 2.29: Near-net shape forming blank in being heated before shape forming [60]

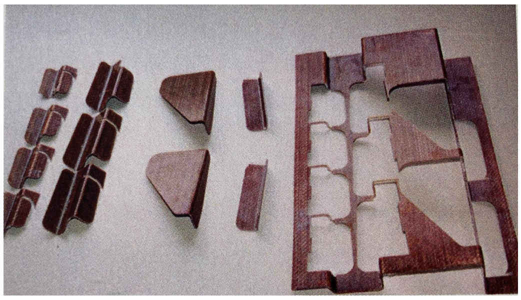


Figure 2.30: Formed sheet with the components milled out [61]

The basic steps of stamp forming include the heating of the blank to its processing temperature, the transfer of the heated blank to the stamp forming tooling, the application of pressure from a die or tool to form the shape and the cooling and removal of the part. This process is illustrated in Figure 2.31.
A stamp forming process can be either isothermal, or non-isothermal. In an isothermal stamp forming

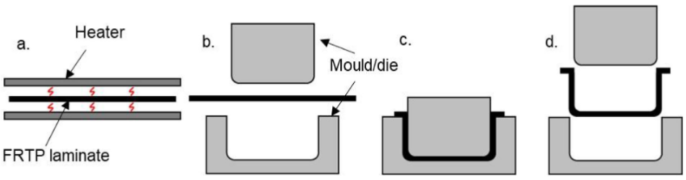


Figure 2.31: Stamp forming process of Fibre Reinforced ThermoPlastics (FRTP) (a). heating of the blank (b). transfer to the tooling (c). shape forming of the blank (d). cooling/removal of the blank [58]

process the laminate and tool are heated to the forming temperature together, and are also subsequently cooled together. This process has a high cycle time, as the moulds need to be cooled and heated for each laminate. For shorter cycle times, a non-isothermal forming process can be used, where the laminate is heated outside the moulds, and the moulds are kept at a lower temperature. When the laminate reaches the forming temperature it is placed in the moulds, formed under pressure, cooled to below the re-crystallisation temperature before the pressure is released and the part is removed. In this way the mould can stay at a single temperature, improving the processing times. The downside of a non-isothermal process is an increase in the number of voids, as the consolidation time is lower [12][62]. An overview of an isothermal stamp-forming process is shown in Figure 2.32, and a non-isothermal process is shown in Figure 2.33. The main process parameters of stamp forming include the temperature of the laminate during forming, the forming speed of the tool, the forming pressure and the cooling rate [58]. The deformation mechanisms of the material and the effect of the process parameters on the quality the parts are further discussed in Section 3.3.

2.3.5. Machining

After shape forming and consolidation, the edges of the parts are trimmed to their final dimensions and any additional holes in the structure are drilled. The drilling is usually done using speciality drill bits, to prevent any damage to the outer layers of the laminate. The trimming of the edges of the components can be done using a saw, milling machine or water jet cutter [38]. For all these methods it is important not to damage the component during trimming, and according to the quantity and geometry a selection can

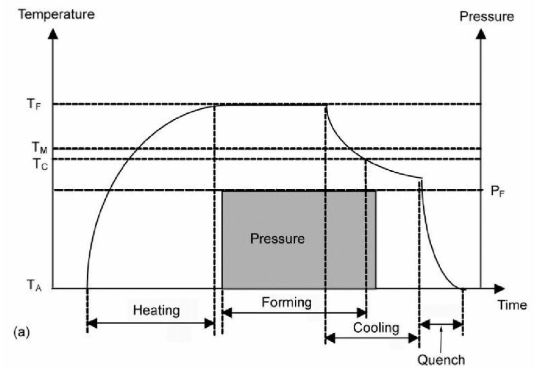


Figure 2.32: Temperature vs time for an isothermal stamp-forming process [62]

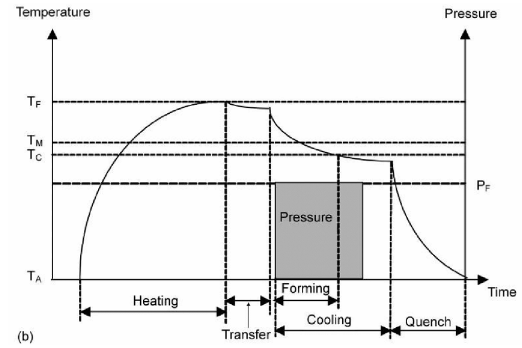


Figure 2.33: Temperature vs time for a non- isothermal stamp-forming process [62]

be made. A 5-axis trimming process of complex thermoplastic composite clips, as shown in Figure 2.35, is illustrated in Figure 2.34 .

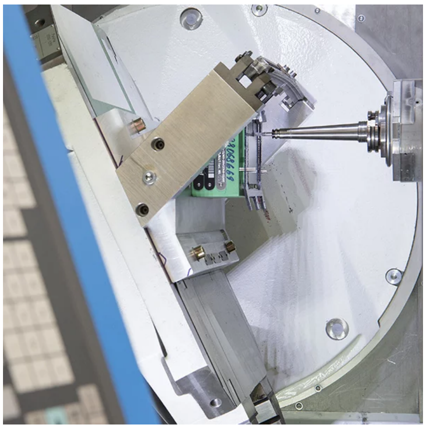


Figure 2.34: 5-axis milling setup trimming the edges of a thermoplastic composite clip [45][60]

Figure 2.35: Complex formed parts after edge trimming [45][60]

2.3.6. Inspection

After machining the components to their final dimensions, the parts are inspected to ensure the reliability and safety of the parts. Aviation authorities have strict regulations around the number of defects that can be present in a parts to ensure this. For instance, the Federal Aviation Authority (FAA) dictates that the maximum size of a delamination should be less than 12.5mm and the void content should be less than 1.0%, whilst the part retains its functionality and structural design properties [63]. Defects can occur during the lifetime of the parts as well, but this section is limited to the defects incurred during production and their inspection methods. Common defects during production are summarised in Table 2.4. Non-destructive inspection (NDI) methods are used to detect defects in the parts, and are used to assure the predefined quality standards of the parts. Common non-destructive inspection techniques used in the Aerospace industry include ultrasonics, radiography and thermography, as these allow for reliable inspection on a large scale [63].

Ultrasonic inspection uses the transmission of high energy ultrasonic sound waves through the material to detect internal defects. Two methods of ultrasonic testing can be used, pulse-echo and through-transmission testing, but the latter is more commonly used for the inspection of as-manufactured parts [63]. Through-transmission testing utilises a transducer on both sides of the material, a transmitting and receiving side, which record the energy levels of the sound waves passing through the material. As this sound wave encounters a defect, its energy is lowered, indicating the presence of a defect. This is shown schematically in Figure 2.36. Using this method, a 2- or 3-dimensional image of the

Table 2.4: Commonly found defects after the manufacturing process of thermoplastic composite parts [63][12]

Defect	Description	Possible reason
Contamination	Foreign particles present inside the material	Forgotten backing foil/tapes from the layup process or intentional material used required for processing
Delamination	Area between plies where they have failed to bond	Incorrect processing temperature, pressure or time leading to poor consolidation, or separation due to residual cooling stresses
Voids	A pocket of trapped air, moisture, solvents or gas within the material	Trapped during layup or consolidation, and not removed due to poor consolidation
Matrix cracks	Crack within the matrix material	Residual stresses in the material during curing or insuficcient temperature during shape forming
Fibre breakage	Breaking of the fibre filament within the material	Machining of the laminate, scratches on the outside surface or a too complex geometry for shape forming
Resin-rich/starved areas	Area with too much or little resin compared to other areas	non-uniform resin distribution within the material, too little resin flow or restricted areas within the part
Fibre misalignment	Misoriented fibres compared to the rest of the ply	Excessive resin flow displacing the fibres due to high consolidation pressure and temperature

material can be constructed where defects can be clearly visible, which is called a C-scan. A C-scan of a carbon-epoxy composite with a defects is shown in Figure 2.37. Ultrasonic inspection can be used to detect internal delaminations, larger voids, clusters of micro-voids and foreign object contaminants [12][63].

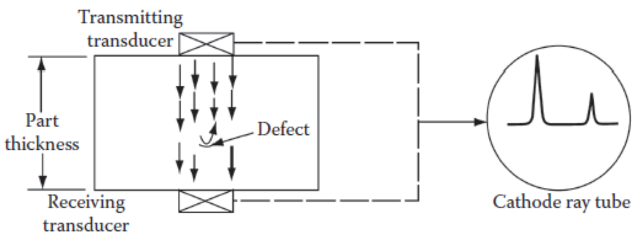


Figure 2.36: Schematic overview of the principle of through-transmission ultrasonic testing, indicating the lower energy of sound wave that passes a defect [12]

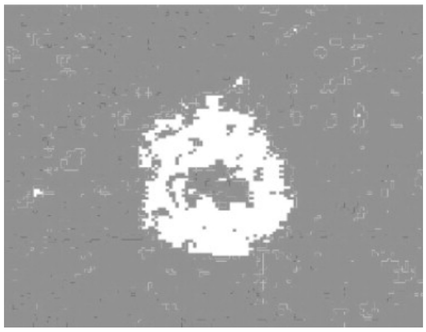


Figure 2.37: C-scan of a carbon-epoxy composite material with an internal delamination visible as a white area, caused by an impact event [63]

Radiography utilises radiation to detect damage within the laminates. Radiation, commonly in form of X-rays for thinner parts and Gamma rays for thicker parts, are emitted from a source and passed throughout the material, which absorbs the radiation energy. Defects, such as air gaps, have a much lower or different absorption rate than the material, which results in a lower amount of energy absorbed throughout the whole passage. The intensity of the radiation is measured on an X-ray film, where the regions of defects would result in a darker or lighter spot compared to defect free regions. For instance, fibre-rich areas would be lighter, and large voids will appear as darker spots. This process is shown schematically in Figure 2.38, and an X-ray of a composite laminate is shown in Figure 2.39. Radiography can detect voids, foreign material contaminations, translaminar cracks, fibre volume distributions and fibre misalignment. Defects such as delaminations are not able to be detected.

Thermography is a method that uses infrared radiation to expose defects within the laminate. Within thermography, both passive and active thermography can be used, where active is more commonly applied. This entails heating the surface of the part through a controllable heating device such as lamps or hot air, heating the surface 10-20° C above the ambient temperature, where the heat is absorbed by the material. If there are any defects present within the material, the absorption of the heat will be hampered at these locations, causing the surrounding regions to absorb more. As the part cools, the

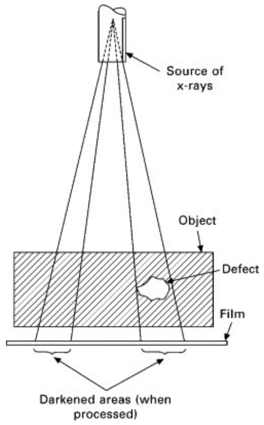


Figure 2.38: Schematic of radiographic inspection that can be used to detect damage in composite materials [63]

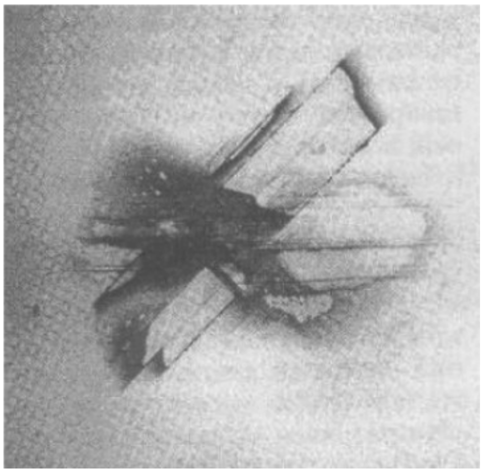


Figure 2.39: X-ray image of a carbon-epoxy material with impact damage [63]

regions surrounding the defect will have a greater heat dissipation, indicating that a defect is present. The heat dissipation can be detected using an infrared camera, making these 'hot-spots' visible. This process is shown schematically in Figure 2.40, and a thermographic image is shown in Figure 2.41. Thermography can be used to detect porosity, delaminations and foreign material contaminations.

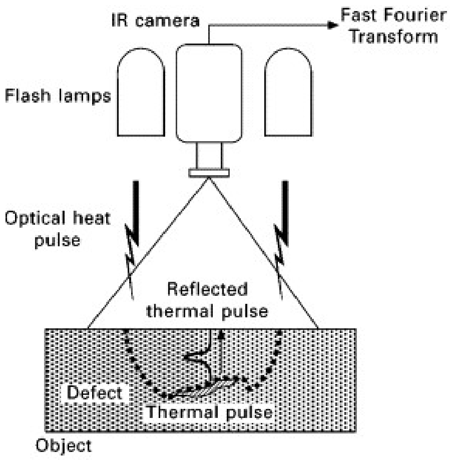


Figure 2.40: Schematic of an active thermographic inspection process [63]

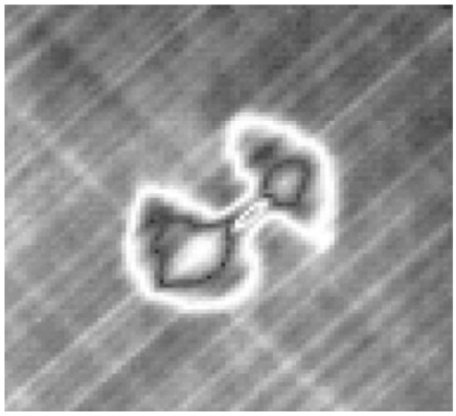


Figure 2.41: Thermographic image of a carbon-epoxy laminate with embedded damage [63]

2.3.7. Future outlook

A future outlook for the manufacturing of thermoplastic composite parts for the aerospace industry has been proposed by T. Slange in his thesis [64]. The future outlook for thermoplastic composite part production is that the material will change from being mostly woven fabric based laminates, to uni-directional tape based laminates [45]. This will allow designers to fully benefit from the ability to tailor the material to its application. Examples of parts currently made from woven fabrics, and the future envisioned parts made from UD material are shown in Figure 2.43 and Figure 2.44. On the processing side, a higher degree of automation is used to maintain high production rates, by using ATL or AFP for the layup step of the parts. In this layup step, full consolidation is not envisioned to keep layup rates high. Using AFP or ATL for the layup also allows for the manufacturing of tailored blanks, reducing the amount of cut-offs of the material from trimming. Consolidation is combined with the shape forming step, in the form of a stamp forming process, where the tailored blanks are shaped and consolidated at the same time. This entire process is visualised in Figure 2.42.

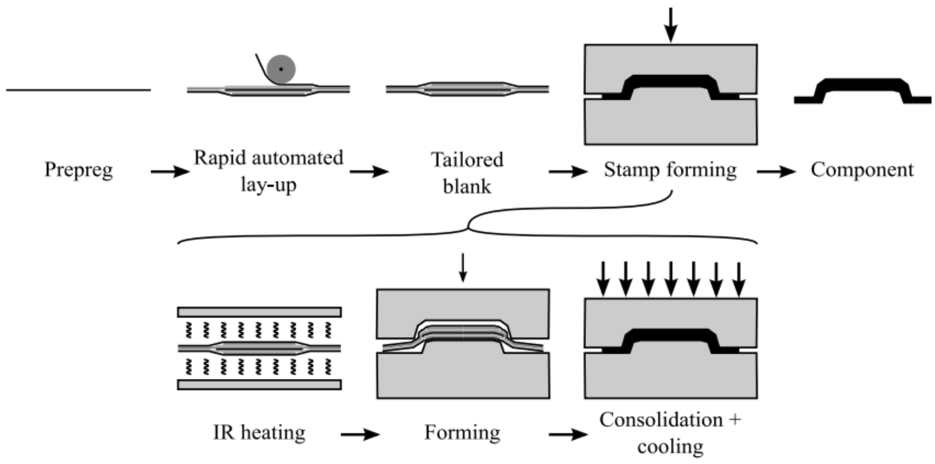


Figure 2.42: Future outlook of thermoplastic composite part production for the Aerospace industry as proposed by T. Slange [64]

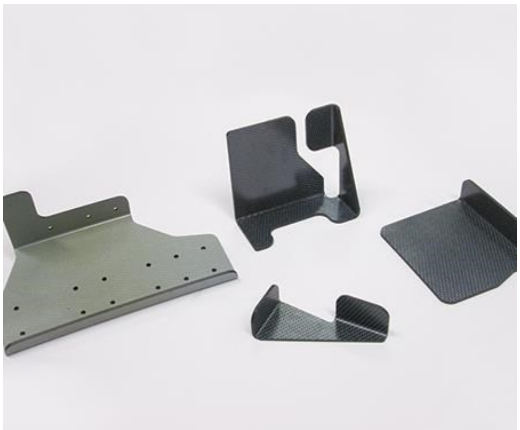


Figure 2.43: Clips, cleats and auto-stabilised structures made from thermoplastic composites for the Airbus A350 [45]

Figure 2.44: Future envisioned clips made from thermoplastic Uni-Directional tapes instead of woven fabrics [45]

2.3.8. Section takeaways

- The thermoplastic composite production process starts with the mixing of the fibres and matrix material, creating the thermoplastic composite material itself
- The layup of the composite thermoplastic material can be done manually or through automation, which is dependent on the required part volume and the complexity of the parts.
- Consolidation of the layup can be done during the layup when using automated layup techniques, or after the layup by using an autoclave or press
- Forming the shape of the part can be done during layup and consolidation if the complexity of the part is relatively low, if using manual or automated layup methods.
- Stamp forming can be used for parts with more complex geometries, and is considered most appropriate for high-rate economical part manufacturing for the aerospace industry.
- A non-isothermal process offers a reduced cycle time compared to a isothermal process for stamp forming, with the downside of increased voids due to a lower consolidation time.
- During processing the size of the part is larger than the net-shape of the final part, requiring machining at the end to obtain its final dimensions.
- Non-destructive inspection of the thermoplastic composite parts is required ensure the manufactured parts comply with standards set by the aviation authorities.
- Ultrasonic inspection methods are commonly used within the aerospace industry to detect defects including delaminations, large voids, clusters of micro-voids and foreign objects.

- A future outlook on the production process of thermoplastic composite parts for aerospace applications suggests that the UD material will replace woven material, automated layup will replace manual layup to make tailored blanks for near-net shape forming and stamp forming is used for forming and consolidation of the tailored blanks to single parts.
-

2.4. Thermoplastic composite production co-products

In this section the term waste is further explored in the framework of the circular economy, exploring the quantities and defining an alternate term. After this, the excess material from the thermoplastic composite production process is further detailed for every step, and a selection is made for the material that will be used throughout the project.

2.4.1. Production co-products

Using the previously established thermoplastic composite production process, all co-products from the thermoplastic composite part production process can be identified. In Figure 2.45 the all production co-products coming from the thermoplastic composite part production process are illustrated. This figure is created using the information obtained during two material manufacturer visits, online press releases of production processes and information found on the websites of part manufacturers [59][61][45]. Within this figure the positive and negative insights of the production co-products are also summarised. A description of each of the production co-products is given in Table 2.5. In the research performed by T. de Bruijn [17], it is found that the majority of the waste found during the manufacturing process is multi-ply consolidated waste, relating to co-products 2 and up [17]. A full detailed description of the co-products can be found in Appendix D.

Table 2.5: Overview of the identified co-products from the thermoplastic composite manufacturing process

Co-product	Description
Single ply off-cuts	Single ply off-cuts created during the lay-up process
Laminate off-cuts	Edges of the laminate that are trimmed off after the consolidation process
Blank cutting remains	Material that remains after blanks have been cut from the consolidated sheets
Post-forming off-cuts	Edges of shaped parts that are trimmed off after the shape forming process
Milling remains	Milled laminate remains resulting from the machining of a part to its final dimensions

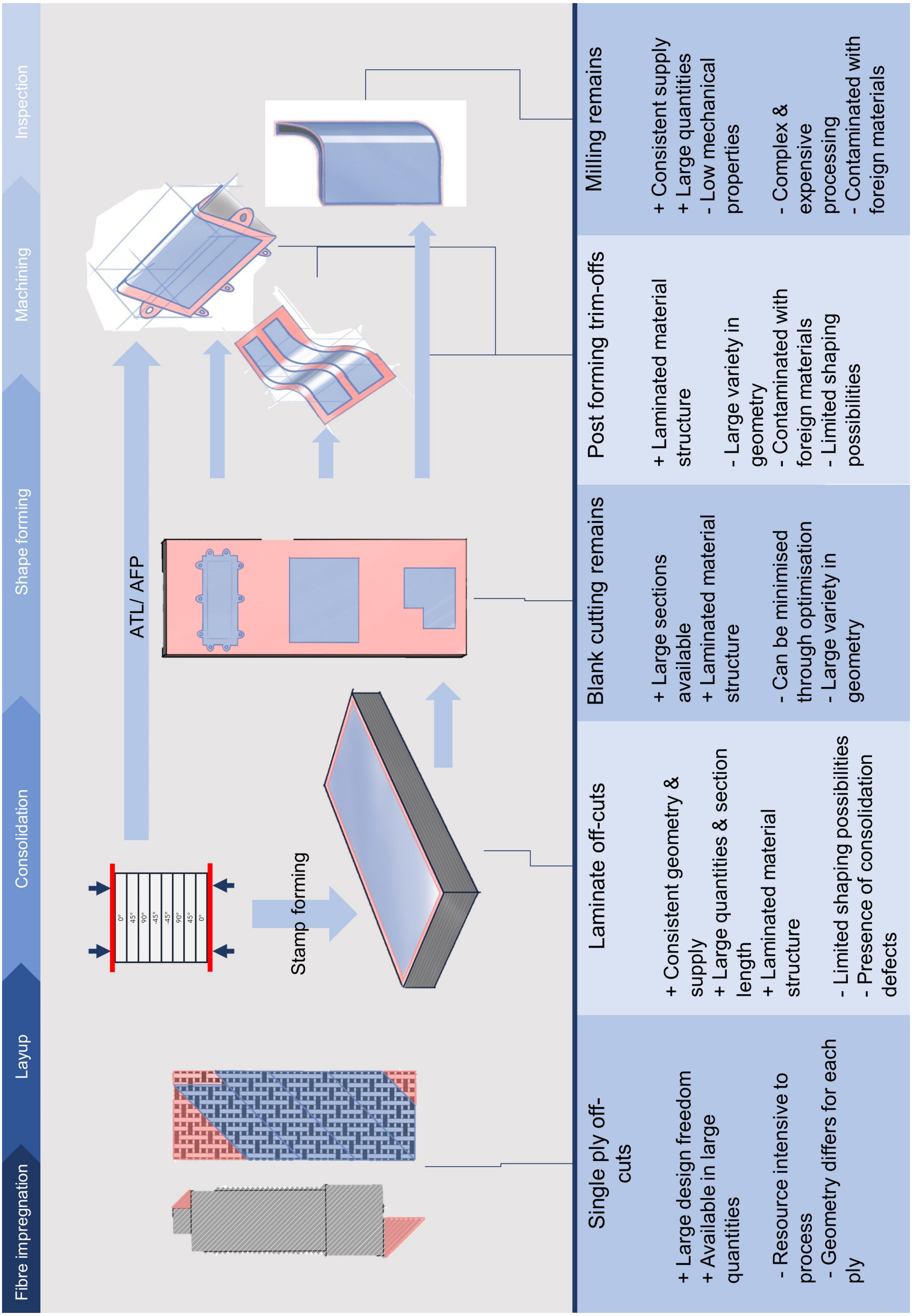


Figure 2.45: Overview of the different types of production waste from a thermoplastic composite forming process for aerospace parts

2.4.2. Selection of co-product

Only one of the identified co-products listed in Table 2.5 is selected for use within the project, to contain the complexity. The selection is based on a set of criteria, which are derived from the constraints of the project, the relevance of the material and the characteristics of the material.

First of all, the material should be recurring from the thermoplastic composite production process, to make this study as realistic and relevant as possible. By taking a one-off waste material from production, the results obtained might not be realistic and therefore less relevant to the real production process. The second is that the material should be available within the time span of the project, to be able to make the results more detailed. Having the material physically allows for studying the material in closer detail, prototyping activities and also have unexpected findings. Furthermore, the material should be free from other material contaminants from production, as this can cloud the results of the study. Composite materials already consist out of multiple materials, and any additional materials or contaminants will increase the complexity by offering new opportunities or limitations. The complexity of processing is the main reason for requiring that the material should be in a multiply consolidated form. Through initial testing with single ply off-cuts, it is found that making a multiply consolidated laminate from this material is highly resource intensive and requires a well established production process. As this project is focused on designing new applications in the form of products, this initial processing step would require too much resources to include. More information on the initial processing test with the single ply off-cuts is provided in Appendix E. An additional criteria used for selection is that the geometry is as consistent as possible. Having a more consistent geometry of material will contain the complexity of processing, and allow the ideation process to be focused on a single form of material, rather than multiple.

These requirements (R) and criteria (C) are coded with an identifier and summarised in Table 2.6.

Table 2.6: List of requirements (R) and wishes (W) used for the selection of a production co-product

Requirement ID	Description
R-MS-1	The production co-product should be recurring from the production process
R-MS-2	The production co-product should be available within the time span of the graduation project
R-MS-3	The co-product should be free from other material contaminants from production
R-MS-4	The production co-product should be in a multiply consolidated form
C-MS-5	The geometry of the production co-product should be as consistent as possible

By studying the characteristics of the production co-products and applying this set of criteria a selection matrix for one co-product can be made, as shown in Table 2.7. All the identified production co-products are recurring from the production process and thus satisfy the first requirement. The blank cutting remains, post-forming trim-offs and the milling remains do not satisfy the second requirement, as there was very limited communication from a company that would be able to supply these materials. This would mean these materials would be available later in the project, which was not acceptable. Both the single ply off-cuts and the laminate off-cuts are largely free from contaminants, and thus satisfy the third requirement. However, as the single ply off-cut is not in a multiply consolidated form, it does not satisfy the fourth requirement. When also including the preference of a constant geometry, the single ply off-cuts also do not meet this as these are supplied in a wide variety of different geometries. The laminate off-cuts meet all the aforementioned requirements, and are also supplied in a relatively constant geometry, and are thus chosen for the remainder of the project.

2.4.3. Section Takeaways

- From the thermoplastic composite part production process, five different co-products can be identified: single ply off-cuts, laminate off-cuts, blank cutting remains, post-forming trim-offs and milling remains.
- Laminate off-cuts are selected as the focus for this project as are a recurring production co-product, available within the time span of the project, free from foreign contaminants, feature

Table 2.7: Application of the selection criteria to the five different co-products, with varying degrees of fulfilment of the wishes with green indication good, orange average and red below average.

Criteria ID	Single ply off-cuts	Laminate off-cuts	Blank cutting remains	Post-forming off-cuts	Milling remains
R-MS-1	✓	✓	✓	✓	✓
R-MS-2	✓	✓	x	x	x
R-MS-3	✓	✓	✓	x	x
R-MS-4	x	✓	✓	✓	x
C-MS-5		✓			

a consistent geometry and are in a consolidated material form.

2.5. Laminate off-cuts

This section describes the laminate off-cuts in more detail, covering the material origin, its geometry, the composite material properties, the quantity, the defects present, the presence of auxiliary materials, its aesthetics and its perceptions.

2.5.1. Material origin

The material used in the project originates from the manufacturing site of Toray Advanced Composites in Nijverdal, the Netherlands. Within this facility thermoplastic composite laminates can be made with up to a maximum 20 layers of composite material [65]. After consolidation, the laminate is trimmed to its final dimensions using a saw and brought to the inspection department, leaving the laminate off-cuts as a remainder. Laminate cut-offs have been generously provided by Toray Advanced Composites for use during this project, and in Figure 2.46 a picture of the laminate off-cuts in the shipment box is presented. Unfortunately, the length of the material had to be reduced to roughly 1500mm for shipping.

Figure 2.46: Cardboard box filled with the laminate off-cuts, made available for use in this project (1500x300x300mm)

2.5.2. Geometry

The laminate off-cuts received for this project present in the form of long strips with a small width. The length of the received laminate off-cuts is in the range of 1000-1500mm, depending on how these are cut. The thickness of the laminate off-cuts can vary from 1-20 plies, which results in a thickness range from 0.23 - 5mm. However, the thickness of the laminate off-cuts received for use in this project ranges from 1.5-5mm. Taking into account the thickness of the layers, these consist of 7 and 22 layers of thermoplastic composite material respectively.
Some of the laminate off-cuts also present with in-plane deformation, possibly caused by residual stress

inside the material from the process, or from the cutting process. This deformation can result in an in-plane deformation of a couple of centimetres over the length of the laminate off-cut.

2.5.3. Composite material properties

The material provided for this project is Toray Cetex©TC1000-PPS, which consists of T300JB carbon fibres in a plain weave and PPS as the matrix material. The layup of the material is quasi-isotropic, as mentioned by the supplier, but there are no records of the layup available. The properties of the material are summarised in Table 2.8.

The strength properties of the laminate off-cuts, as presented in Table 2.8 , have been lowered using knockdown factors to account for the defects present in the material. The effect of porosity, delamination and impact damage on the compression strength has been described by Whitehead [66], as shown in Figure 2.47. A knockdown factor of 0.65 is used for the porosity, as the squeezed out resin particles at the side of the laminate indicate that porosity might have migrated to the edges of the laminate. A knockdown factor of 0.65 is used for the delamination, as delamination is observed at several locations of the laminate off-cuts. A factor of 0.8 is used for the impact damage as the handling of the laminate off-cuts is unknown, and it could be possible that these have been dropped and or knocked against objects. The same knockdown factors are used for the tensile and shear strength of the material, to ensure that these are also reduced accordingly. More information on the defects observed in the laminate off-cuts is given in Section 2.5.4.

Table 2.8: Selected properties of TC1100-PPS material as provided by Today Advanced Composites [46]

Material Property	Magnitude	Unit	Material Property	Magnitude	Unit
Fibre areal weight (FAW)	200	$\frac{g}{m^2}$	Tensile strength 0° (S_{TP-t-1})	254.5	Mpa
Weight per ply (PAW)	255	$\frac{g}{m^2}$	Tensile modulus 0°	55.9	Gpa
Resin content	43	%	Compressive strength 0° (S_{TP-c})	193	Mpa
Density	1.55	mm	Compressive modulus 0°	51.9	Gpa
Consolidated ply thickness (CPT)	0.23	mm	In-plane shear strength $\pm$ 45 (S_{TP-ips})	42	Mpa
Fabric width	1270	mm	In-plane shear modulus $\pm$ 45	3.9	Gpa
T_g (glass transition)	90	° C	Flexural strength 0°	303	Mpa
T_m (melt)	280	° C	Flexural modulus 0°	49	Gpa
T_p (processing)	300-330	° C			

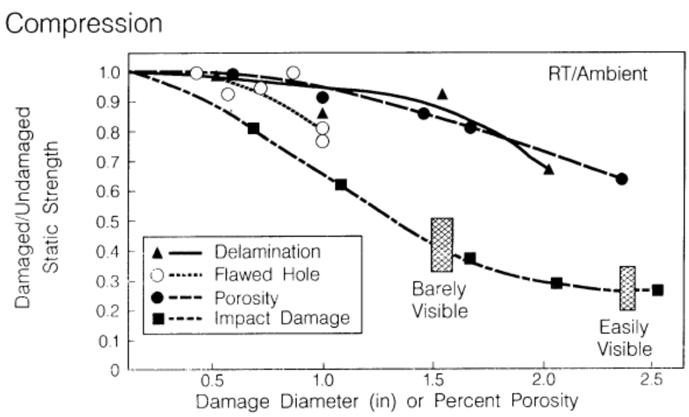


Figure 2.47: Effect of delamination, flawed hole, porosity and impact damage on the compression strength of composite material [66]

2.5.4. Defects
The material has been visually inspected for defects, of which a description and their possible effect on the material properties is given in Table 2.9, and a more detailed description can be found in Appendix F.

2.5.5. Auxiliary materials

Auxiliary materials are materials that are added to the composite material to ensure that it can meet additional requirements that the composite material cannot meet. In the case for composite materials for aerospace applications these can include protection against galvanic corrosion in the form of a small layer of glass fibre, lightning strike protection in the form of a copper mesh, or a coating to protect against the environment. The obtained laminate off-cuts for the project do not contain any of the aforementioned auxiliary materials, but these could be present in future scenario's.

2.5.6. Aesthetics

The aesthetics of the laminate off-cuts are considered on a material level by studying the material closely, and placing this in different settings. The material is examined for three out of the five senses: touch, sight and hearing. Smell and taste are omitted from this analysis.
The first setting was an analysis in a lab where the sight of the material was inspected visually, the touch was examined using both gloves and bare hands and the hearing was examined through flicking of the nail against the material and hitting this against a metal surface. A close-up look at the material is presented in Figure 2.48. From this it is observed that the material has a bluish colour, caused by the white/yellow colour of the matrix between the fibres and the black colour of the carbon fibres. Furthermore, the pattern of the carbon fibres causes a visible black textured pattern, which can not be felt through touch. Also, the material feels cold to the touch, and when hit it produced a high-pitched ringing noise.

To study the sight of the material in an outside condition the material was brought outside, where its reflection in the sun could be observed. The reflection of the carbon fibre and the matrix material was not the same, and presented in a diffuse pattern, changing the colour of the material locally. This effect is demonstrated in Figure 2.49.
The aesthetic properties of the material are summarised in Table 2.10, and can be used within the design process to convey a specific message, e.g. this material looks expensive or this material feels cold.

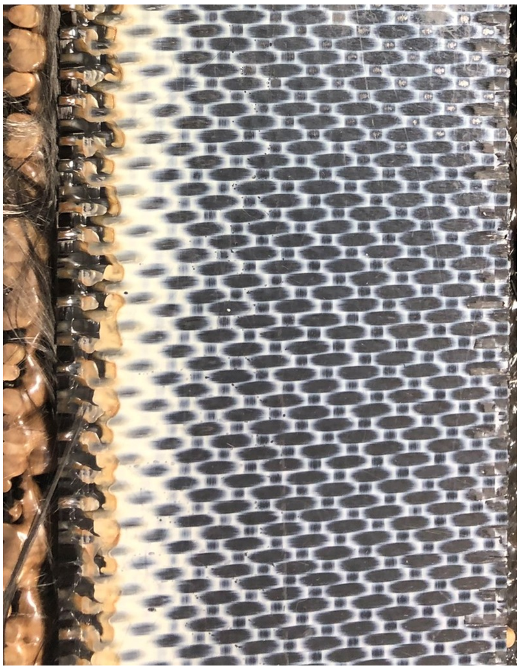


Figure 2.48: Close-up of a laminate off-cuts, demonstrating the color gradient and textured pattern of the woven carbon fibres

Figure 2.49: Scattered reflection of the sun on the laminate off-cuts, with the sun affecting the perceived colour of the material

Table 2.9: Summary of the defects found in the laminate off-cuts by visual inspection

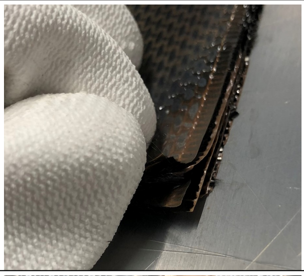
Defect	Description	Image
Thermal degradation	Darker resin spots due to thermal degradation causing microcracks, voids, delaminations and a reduction of mechanical properties	
Resin squeeze out	Resin squeezed out of the laminate due to high temperature and pressure, causing resin starved areas that affect matrix dominated mechanical properties	
Foreign material contamination	Contamination of the material with foreign materials used in processing, little effect as these are present on the outside of the material	
Dry spots	Round 'dry' spot with and fibre misalignment inside and around, causing degradation of the mechanical properties and can act as an initiation site for damage to the fibres	
Material warpage	In-plane warpage of the material along the length of the laminate off-cut, possibly caused due to residual cooling stresses in the material	

Table 2.10: Aesthetic properties of the carbon/PPS laminate material used in the laminate off-cuts

Sense	Touch	Sight	Hearing
Attributes	cold, hard, stiff	opaque, reflective, glossy, texturedblue, white and black	sharp, ringing, high-pitched

2.5.7. Perceptions

The perceived attributes of the laminate off-cuts are important to know, as this can affect how a product made from laminate off-cuts is perceived by the users. To explore the perception of the laminate off-cuts a vocabulary of perception can be used, which is a list of terms that are used to describe products [67]. Determining the perception of the material is subjective, and is in this case based on the author's own perceptions, and the perceptions of fellow students.

The laminate off-cuts can be perceived in two ways, either it is considered a very valuable material or as a waste material. The material of which the laminate off-cuts consist, carbon fibre and PPS thermoplastic matrix, are materials of a high value which are used in high-end applications. This makes the perception of these materials expensive, exclusive, lasting, modern and futuristic. However, when in the form of laminate off-cuts, the material is considered as a waste material, changing the perception to cheap, disposable and dull.

This contradicting perception of the laminate off-cuts can be used within the design process, highlighting either of these perceptions.

2.5.8. Section takeaways

- The length of the laminate off-cuts that are made available for the project range from 1000-1500mm
- The thickness of the laminate off-cuts varies from 7-22 layers, 1.5-5mm
- The laminate off-cuts present with local delaminations, dry spots and resin squeeze out, and foreign material contamination which result in a reduction of the mechanical properties by a factor 0.338 based on literature
-
- The aesthetics of the laminate off-cuts are based on a blend of the experiential properties of the matrix and of the fibres, which can be observed optically as a gradient like effect in the reflection of the sun
- The perception of the laminate off-cuts is two fold, either seen as valuable or as a waste material, depending on whether its original function or current state is highlighted.

3
Exploring processing of thermoplastic composites

3.1. Introduction

The nature of thermoplastic composite materials allow it to be shaped to any form. The shaping possibilities of the laminate off-cuts are endless, but no functionality or intent is currently foreseen for the material that can drive the shaping. This principle is also used in product design, ”form follows function”,where the functionality of the product determines its form. Within this project a different approach is taken, first exploring the possibilities, and then finding a form that makes use of the properties of the material. In this case ”form follows material”. Firstly, options for shaping and assembly of laminate off-cuts are explored, along a varying degree in Section 3.2. An initial processing scope is created at the end of this section, to align with the scope of the project. The shaping and assembly steps that are within the scope of the project are further detailed in Section 3.3 and Section 3.4, which contain the basis for the manufacturing of the material form.

3.2. Degree of shaping and assembly

The shaping of thermoplastic composite materials is driven by temperature and pressure, as described in Section 2.3.4, and as long as this can be applied to the material almost any form can be created. The laminate off-cuts have a very distinct geometry, long slender strips, and the direct use cases in which these are limited. To create more opportunities, the strips can be assembled together to create new forms either with better functionality or larger dimensions. As such, both shaping and assembly are considered together in this section. The degree of shaping and assembly is variable, from simple processing steps to more complex forming operations. In Figure 3.1 an overview is made of the varying degrees of shaping and assembly, where these are first seen as separate processes, and in more complex processes these are combined. Very complex shaping methods such as forging also have their limitations: As the degree of shaping and assembly increases, the part and process complexity increase but the material integrity and re-usability decrease. In the next subsections , each of the identified processing methods is further detailed through a short description of the process, the potential applications for design, the tooling required and the limitations of the process.

3.2.1. Single bend forming

Single bend forming is the forming of the laminate off-cuts over a single axis, into a bend with a specified radius and angle. This method is currently used in the aerospace industry to form bend for attachment points for clips, as shown in Figure 2.43, or to ’fold’ a thermoplastic sheet into a rudder trailing edge as shown in Figure 3.2.

Depending on the application, single bend forming can either be done using a closed mould process, utilising a mould to form the bend into a specified geometry, or without a mould where the material collapses upon itself as shown in Figure 3.2. As a result, the tooling required for the process is relatively simply, requiring only a heat source, mechanism to apply the bend and a mould to which the material can comply to under pressure, if the bend has strict mechanical requirements.

The part complexity that can be achieved with single bend forming is relatively low, but it opens up the out of plane bending dimension to the design freedom. The single bend forming process is limited

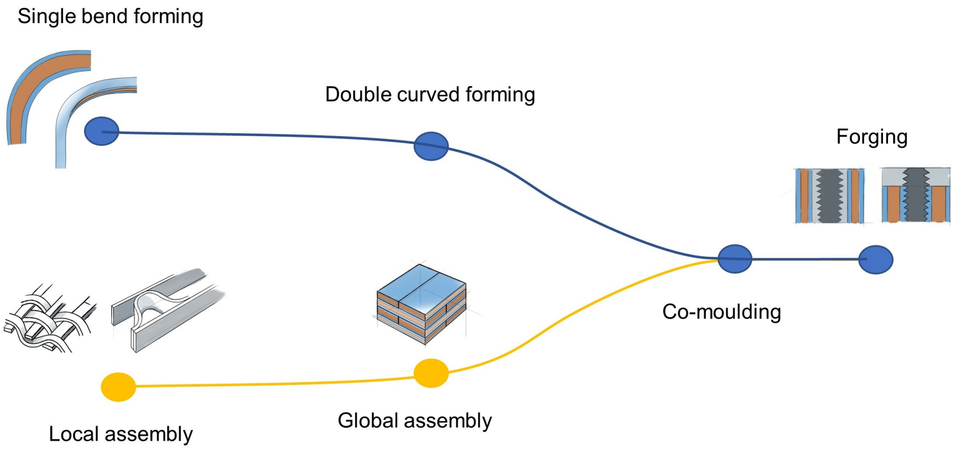


Figure 3.1: Varying degrees of shaping and assembly of the laminate off-cuts

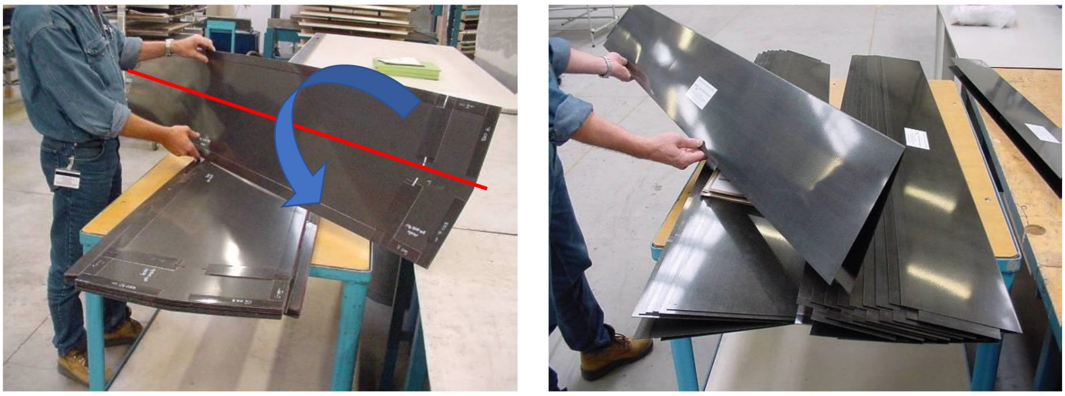


Figure 3.2: The single bend forming 'folding' of a CF/PEI thermoplastic sheet to a rudder trailing edge for the G650 aircraft [18]

by the bending radius, bending angle and the processing parameters of the material, which are further explored in Section 3.3.

3.2.2. Double curved forming

Double curved forming is the forming of a material over a surface that curves in two directions, e.g. a dome or a sphere. This type of forming is common for fabric based materials, and can be used to manufacture complex forms as shown in Figure 3.3.

When considering a single laminate off-cut, double curved forming can be achieved in the manner as described before, bending in two directions simultaneously, but also through shaping the strip over a cylinder or rotating it along its longitudinal axis. This would entail shearing the material in multiple directions, whilst also bending over another axis. To shape the laminate off-cuts in two directions a closed moulding process can be used such as for single bend forming, but also an out of mould process can be used where the material is held under tension, heated and draped over a mould to form a double curved shape. The double curved forming process opens up additional dimensions to the design freedom, allowing for multiple directions to be utilised at the same time. However, due to the more complex shaping of the material the material integrity can be reduced due to the additional deformation mechanisms of the material.

3.2.3. Local assembly

Local assembly describes the joining of two materials/structure on a small interface. Within the aerospace industry local joining is used on stiffeners and the skin of the Airbus A380 J-Nose, as shown in Figure 3.4. Through local assembly relatively simple components can be joined together, opening up the possibility

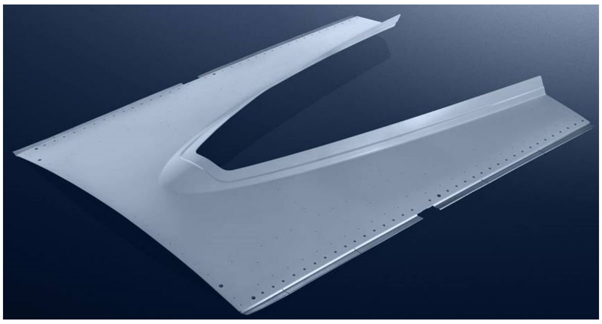


Figure 3.3: Engine pylon cover of the A380 with double curved features made from carbon fibre/PPS composite material [68]

to create larger or more complex structures.

Local joining can be done using permanent or reversible methods, where the application of the struc-

Figure 3.4: Local joining of the A380 J-Nose ribs with the skin using resistance welding [18]

ture determines which is more suitable. For reversible connections the repair, replacement and re-usability at end-of-life of the structure is easier when comparing this to permanent connections, which can only be separated through destructive methods. The tooling required for local assembly consists of a mechanisms to align the parts that need to be joined and a mechanisms that can apply the pressure. For this relatively simple jigs can be used in combination with off the shelf glue clamps to apply the pressure. Local assembly of the laminate off-cuts is limited by the available space for joining, considering the width of the strips, and the mechanical properties of the connection method. The joining methods for thermoplastic laminate off-cuts are further detailed in Section 3.4.

3.2.4. General assembly

General assembly is described as the joining of material over its entire surface within the scope of this report. For the case of laminate off-cuts, this would entail placing the off-cuts side by side and in a stacked form, and joining them over their entire surface. This method can be used to create a larger panel or beam out of smaller elements, which could be used for subsequent forming steps or as-is. An example of this is shown in Figure 3.5.

The difference with local joining is that in general assembly the material is joined over its entire surface, rather than the locally. In this way, it opens up the possibility to create larger or thicker structures from multiple laminate off-cuts, that can be used in subsequent shape forming steps. General assembly of the laminate off-cuts can be realised through consolidation, adhesive bonding or attachment using fasteners. As such, the complexity of the general assembly can vary depending on the application, where consolidation would require the most complex tooling and mechanical fasteners the least. This method is limited by the geometry of the strips, as these need to match and make it hard to isolate a single laminate off-cuts for repair, replacement or re-use at the end of life.

3.2.5. Co-moulding

Co-moulding is defined as a process where two separate components are joined together through the use of a closed moulding process within the scope of this report. This entails that the process is taking

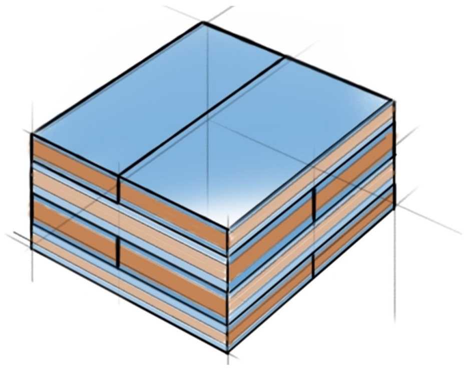


Figure 3.5: General assembly of the laminate off-cuts into a larger discontinuous structure

place within two closed moulds, where consolidation between the two separate components occurs due to an applied heat and pressure. One example of co-moulding is shown in Figure 3.6, where continuous fibres are co-moulded with short fibre composites to act as a core material or to create new features that could not be moulded with continuous fibre composites. An example that is relatable for

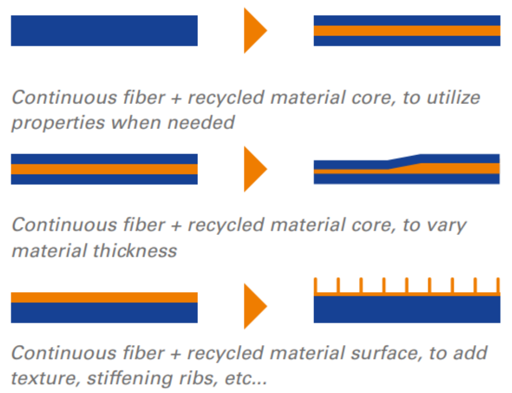


Figure 3.6: Example of co-moulding of short fibre composite and continuous fibre composites [29]

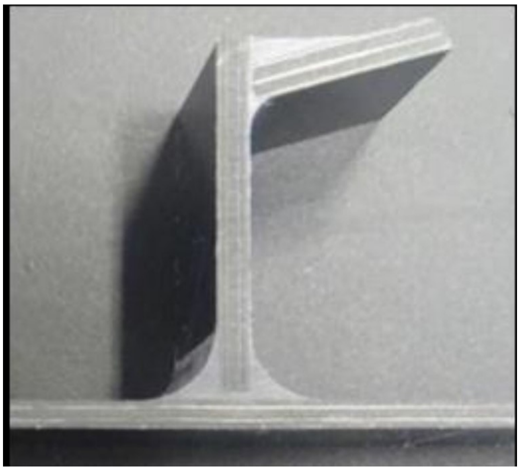


Figure 3.7: Stiffener made using a co-moulding process of several continuous fibre reinforced structures and a short fibre injection moulding compound [18]

the laminate off-cuts is the use of continuous fibre structures as in-lays in this process, where they provide the strength and stiffness of the structure and a filler is used to join everything together. The cross section of a stiffener using such a process is shown in Figure 3.7, where flat strips are used as in-lays in the mould, and a short fibre injection moulding compound is used to create the bond geometry between the in-lays. The co-moulding process uses closed mould tooling that is specifically designed for the to be moulded structure, which can quickly become complex and costly. This process maintains the integrity of the material, but makes it hard to separate the components during or after the life of the structure.

3.2.6. Forging

Forging of thermoplastic composite materials is similar to compression moulding, where chopped fibre sections are placed inside a mould, heated and compressed to follow the contours of the mould [69] [70]. An example of a forging process is shown in Figure 3.8, where a rolled strip consisting of long fibre sections is used as a preform. In the case for this project, the process is envisioned to use the laminate off-cuts are preforms, which are then 'forged' to complex shapes. Using this process, complex parts can be made, with included features such as holes and threads, as shown in Figure 3.9. The tooling for this process is complex, requiring a set of closed moulds that are machined to a high tolerance, similar

Figure 3.8: Example of a preform loaded into a forging mould [69]

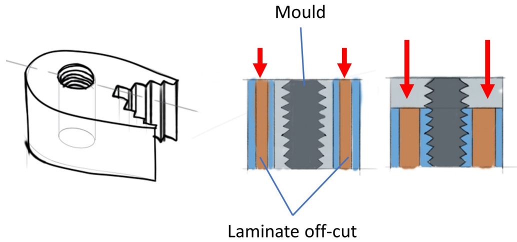


Figure 3.9: Complex part manufactured using the laminate off-cuts as preform material

to that of co-moulding. Within this process the material integrity is lowered as the material is forced to comply with the mould surface due to the high applied pressure, breaking the fibres in the process. The part complexity is the highest that can be achieved out of all the shaping processes, but it requires the most complex tooling, and reduces the material integrity the most.

3.2.7. Initial shaping focus

After exploring the possible options for shaping and assembling the laminate off-cuts, an initial shaping focus is defined to contain the complexity of the processing to be able to explore it in more detail throughout this project. This focus is based on requirements, which are determined from limitations of the project duration, the available equipment and the implications for the design freedom of the shaping method.

Firstly, the shaping method should not be feasible to achieve within the project time, and be possible through using the equipment available. It is not possible to design very complex tooling within the time-frame of the project, due to the extensive amount of resources that is required, which would also constrain the exploratory nature of the project. Secondly, the material should retain as much of its integrity as possible, to ensure that it retains its structural performance. If the integrity of the material is reduced significantly it will lead to downcycling, negatively affecting its opportunities for re-use in subsequent life-cycles. Furthermore, the processing method should allow for a large design freedom, to ensure that enough opportunities with the material can be explored within the project. If the scope is taken too narrow, there shaping possibilities can be too limited and constrain the results.

These requirements are summarised in Table 3.1, and by using the information on each of the shaping opportunities a selection matrix is made. This matrix summarises the applicability of a shaping method to a requirement . The boundary is based on several criteria, mostly coming from limitations of the project and some in line with circular composite design guidelines. The criteria are summarised in table Table 3.1.

Table 3.1: List of requirements (R) and wishes (W) used for the selection of a processing method

Requirement ID	Description
R-PS-1	The processing method should not require expensive and complex tooling that is not available at the faculty of Aerospace Engineering and Industrial Design Engineering
R-PS-2	The processing method will retain the integrity of the material
R-PS-3	The processing method should allow for a large design freedom

From these criteria it is determined that the initial focus of processing the laminate off-cuts includes single bend forming and local assembly. These methods use relatively simple tooling that can either be made within the time-frame of the project, or is readily available at both faculties. Furthermore, these methods retain most of the integrity of the material, as they only act locally on the laminate off-cuts. Using both local assembly and single bend forming also opens up a large design freedom that is deemed suitable for this initial exploration.

3.2.8. Section takeaways

- Laminate off-cuts can be processed into complex forms and shapes through a reduction of the material integrity.
- The initial processing focus of the laminate off-cuts is put on single bend forming and local assembly, as these methods can be explored in more detail throughout the project.

3.3. Single bend forming

Within this section the single bend forming of thermoplastic composite materials is further explored to gain insights into the underlying mechanisms, processing parameters and tooling that is required. This information is required for the manufacturing of the beam structure from the laminate off-cuts. First, the deformation mechanisms of the material are detailed, and their dependencies on the processing parameters are discussed. Next, possible defects from the forming process are discussed, as well as ways to mitigate these. From visits to manufacturers, literature and patents a list of forming equipment that can be used to make single bends is created. Finally, a table with the recommended parameters for the forming of single bends with the laminate off-cuts is created.

3.3.1. Deformation mechanisms

The deformation mechanisms present during thermoplastic composite forming are summarised in Figure 3.10. The forming of double curved bends is considered out of scope for this study, and the focus is put on single bend forming.

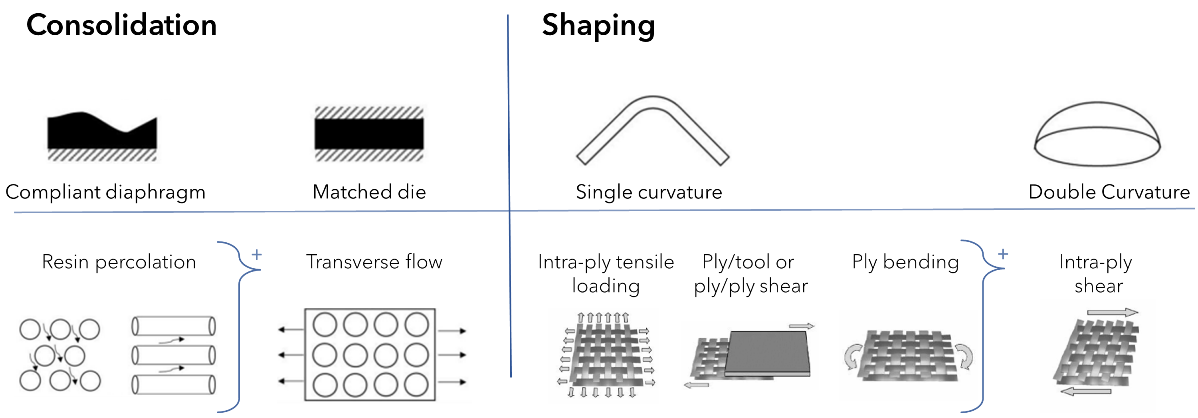


Figure 3.10: Overview of the deformation mechanisms present during consolidation and for various deformation modes. Adapted from [62], [58] and [31]

Resin percolation is the act of resin flowing through the laminate, which is essential for fibre impregnation, evacuation of air from within the laminate, and creating a resin rich layer between the layers, distributing the resin evenly throughout the laminate [12].
The main factors affecting the resin percolation are the viscosity of the matrix and the permeability of the fibre network [58]. For fibre networks, the layup also affects the permeability of the layers within the laminate. Compared to a uni-axial layup, a 45° orientation of the ply above can lead to a 25% reduction in permeability, and a cross-ply layer can even lower this with 50% [31].

Transverse fibre flow occurs when a normal pressure is applied to the laminate, causing resin together with UD fibre bundles to flow sideways and away from where the pressure was applied. There is little axial flow of the fibres due to a higher resistance to flow along the length of the fibres [12].
The transverse flow of the resin is governed by temperate, layup and pressure, where at high temperatures and pressure this can lead to (local) thinning of the laminate, and resin bleed out. This effect is predominantly present in UD based laminates, as the intertwined structure of woven fabrics restricts the flow in the transverse direction [58].

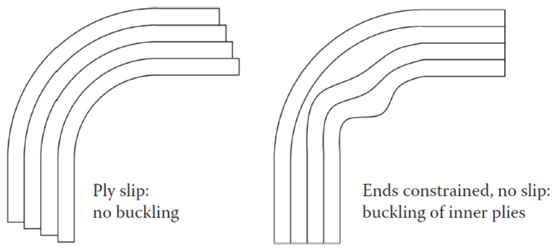


Figure 3.11: Left: Interply slip within layers during forming. Right: No interply slip during forming, edges are constrained [12].

Axial loading is the loading of the fibres in the longitudinal direction during process. This deformation mode is governed by the strength, stiffness and cross sectional area of the fibres used, as high axial loading can cause fibre breakage during processing. Generally, the loading leads to relatively small strains, due to the high stiffness of the fibres used in Aerospace composite structures[62]. However, axial loading can be key within the forming process to restrict fibres from out of plane buckling and forming wrinkles [12].

Interply slip is the sliding of the ply relative to the tool or other plies during the forming process. This deformation mechanisms is especially important during single bend forming, as this is a dominant factor to prevent ply buckling and wrinkling. The effect of interply slip during single bend forming is shown in Figure 3.11 [12]. For interply slip to occur, the interlayer shear yield strength has to be exceeded, where at higher temperatures the thermoplastic matrix can act as a lubricant, reducing the friction. This interlayer shear yield strength is dependent on the temperature, pressure, and forming speed during the processing, as well as the layup of the laminate [12]. The inter-ply shear stress and inter-ply friction can be reduced by adapting temperature, pressure, forming speed and layup angle, and an overview of their effect is summarised in Table 3.2.

Ply bending is the bending of a ply during the forming process, and is the only deformation mode required to bend a single ply. The out of plane bending stiffness of fabric (or UD) materials is significantly lower than the in plane stiffness, due to the possibility of fibre slippage within the tows [62]. The out of plane bending stiffness is driven by the thermoplastic matrix, and is forming rate and temperature dependent. The bending stiffness of UD laminate is a magnitude higher than woven fabrics, but the overall magnitude of the out of plane bending resistance is several magnitudes smaller when compared to other deformation modes [62][71].

Consolidation is the compaction of the thermoplastic composite laminate at an elevated temperature, to increase the fibre volume fraction and eliminate voids. Consolidation is dependent on temperature and pressure, due to the high viscosity of the thermoplastic material [62].

Table 3.2: Summary of the effects of temperature, pressure, forming speed and layup on the interply shear stress and the tool/ply friction [58]

	Shear stress		Friction	
	Ply-ply	Tool-ply	Ply-ply (μ_{pp})	Tool-ply (μ_{tp})
↑ Temperature	↓	Inconclusive	↓	Inconclusive
↑ Pressure	↑	↑	↓	↓
↑ Speed	↑	↑	↑	↑
↑ Angle between fibre/warp direction and sliding direction	↓	↓ or no change	↓	↓ or no change

3.3.2. Forming defects

Chen et al. defined 4 types of defects that can occur during the forming process: In plane undulations/waviness, wrinkling, spring-in or warpage and thickness variation [72]. An illustration of these defects is shown in Figure 3.12.

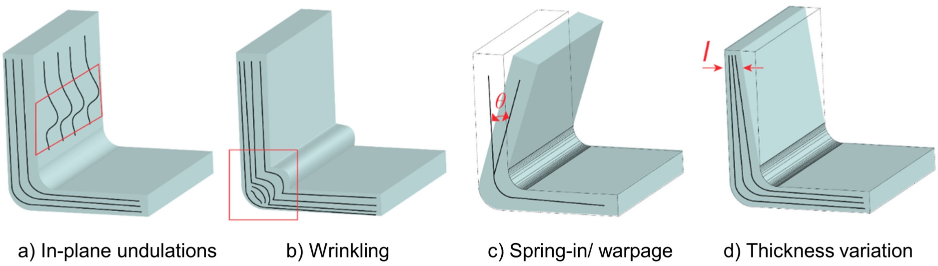


Figure 3.12: Illustration of the different types of forming defects as defined by Chen et al [72].

In-plane undulation, or waviness, describes the deviation of the fibre orientation along its length. Main reasons for this include the movement of adjacent fibre yarns, or a compressive force acting on the ends of the yarn, causing it to move in plane. In plane undulations of unidirectional plies can result in lower compressive strength of the material due to pre-imposed kinking of the fibres [73]. In-plane undulations are dependent on the forming temperature, pressure, speed, bending stiffness, thickness of the material and boundary conditions of the material during processing [72]. The effect of the thickness is demonstrated in Figure 3.13, where the additional thickness (at the same tool radius) creates a larger excess length over a constrained section, leading to in-plane undulations or wrinkling to compensate for this [74]. The temperature, pressure, speed during processing can be increased to reduce the in-plane undulations of the fibre yarns in some cases, and a change in ply stacking could alleviate some of the excess length over a constrained section [74] [75].

Wrinkles are one of the major defects within formed thermoplastic composite components and can lead to fibre breakage over the formed area, leading to lower structural performance. Wrinkles are formed due to an in plane compressive force, and if less energy is required for out of plane bending than in-plane deformation a wrinkle occurs [58]. This is demonstrated in Figure 3.14, where a load along the 0° fibre direction causes in-plane undulations for a 0° ply, and out of plane bending for a 90° ply. The out of plane bending stiffness of the material, together with the inter-ply friction and inter-ply shear stress play a large role in the formation of wrinkles, and can be controlled by the processing parameters as shown in Table 3.2. The effect of increasing the temperature has been shown in two cases, resulting in in-plane undulations rather than wrinkles in a constrained forming situation [76][77]. In terms of the material and tool parameters, the material thickness, layup and forming radius have an effect on the formation of wrinkles, where the forming radius (R) over the thickness of the material (t) can be increased to make this effect less. A $\frac{R}{t} = 3$ is recommended for optimal mechanical properties [78][79]. Wrinkling of the of the surface plies can be reduced through axial loading of the fibres during process, restricting the out of plane movement[12][62]. This method has been applied by Kiss et al. to reverse form thermoplastic composite fabric blanks with defects back to flat blanks without defects[80].

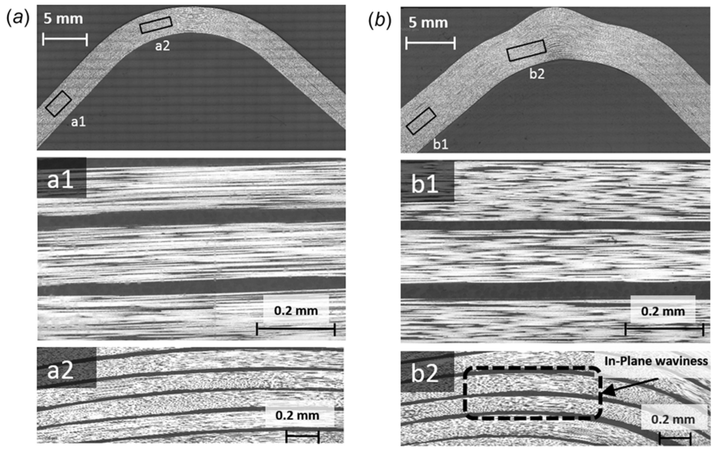


Figure 3.13: Localised in-plane undulations present in (a) 4mm thick sample with increased severity for a (b) 6mm thick sample

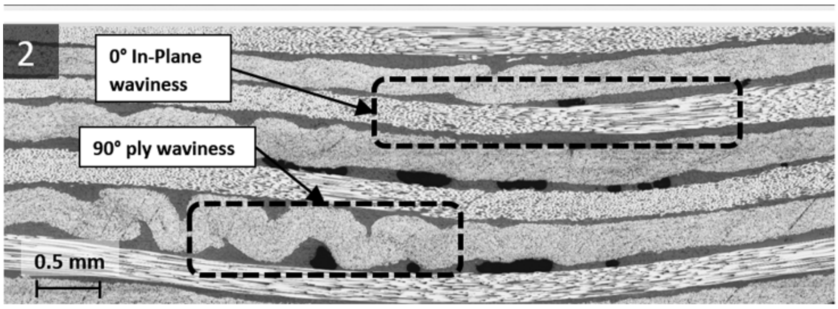


Figure 3.14: In-plane undulations for a 0° ply, and wrinkling of a 90° ply under a 0° applied load

Spring in, or warpage, of formed parts is created due to residual stress within the material upon cooling, creating distortion or warpage of the part. This residual stress within the material created by the variation in coefficients of thermal expansion (CTE) in the circumferential and thickness direction, creating uneven stresses upon cooling . Main contributors to the spring in effect are the CTE of the resin and fibres, and the crystallisation shrinkage of the resin [72]. The spring in-effect can be controlled by increasing or decreasing the mould temperature during forming and cooling of the material [81].

Thickness reduction within formed thermoplastic composite parts is mainly caused by the movement of the fibre bundles and transverse flow of resin. The applied pressure and temperature are considered to be the main contributors to this defect. Local thinning of the part is especially found at the location where the forming tool reaches the part first, creating an uneven pressure gradient and flow of material away from this point [72]. Thickness variations can be prevented by designing the forming tools in such a way that an even pressure distribution is created during the forming process.

3.3.3. Processing parameters

With the forming mechanisms and possible defect mitigation strategies known, it is possible to define the process parameters for the single bend forming of the laminate off-cuts. To compile these parameters, the material manufacturer was asked to provide the recommended processing parameters for the stamp forming process. To add to these recommended parameters, tooling design guidelines from the manufacturer were also reviewed [61][82]. Additionally, a recommendation is made for the forming radius over the thickness ratio, based on a literature review covering the forming of constrained and unconstrained single bend forming. A full list of the reviewed literature can be found in Appendix G. A summary of all the recommended processing parameters for the laminate off-cuts is presented in Table 3.3.

The processing parameters, as presented in Table 3.3, form the basis for the conceptual design of a structure made from the laminate off-cuts, and detail how the material should be processed to form high-quality bends. This table is specifically tailored to the Toray Cetex©TC1100-PPS material, and should be adapted in case another material is used. The processing parameters related to the material, such as the processing temperatures and pressures, could also form the basis for exploring other forming methods rather than single bend forming. However, if high-quality defect free shapes are to be created using these other processing methods, the deformation mechanisms, suitable tooling and geometrical guidelines for these forming methods should be explored further.

Table 3.3: Recommended processing parameters for the single bend forming of the laminate off-cuts [61][82]

Parameter	Magnitude	Unit	Parameter	Magnitude	Unit
Blank temperature	330-350	[\deg C]	Mould material	metal - metal	[-]
Transfer time	<5	[s]	Radius / thickness	3-5	[-]
Mould temperature	200 \pm 10	[\deg C]	Minimum forming radius	5.1	[mm]
Closing speed	10-100	[mm/sec]	Drying time	4	[hours]
Forming pressure	5-50	[bar]	Drying temperature	95	[\deg C]
Time under pressure	60-180	[s]			

3.3.4. Process Equipment

For the forming of single bends in the laminate off-cuts it is also necessary to know what equipment can be used to do this. To get an overview of how this is currently done for thermoplastic composite materials, single bend forming equipment was analysed from literature, thermoplastic composite part manufacturers from aerospace and patents. A summary of the equipment found during the review is given in Figure 3.15, where a division is made between general stamp forming equipment and local single bend forming. The full review of the processing equipment can be found in Appendix H

The summary of the processing equipment, as presented in Figure 3.15, can be used as a guide to explore suitable processing equipment for the laminate off-cuts. It is clear that there is variety in the complexity of the tooling that is used in each stage of the process, where a selection can be made on the available resources and equipment at that point in the project.

3.3.5. Section takeaways

- Interply slip is the dominant deformation mechanism in single bend forming, and can be controlled through the temperature and pressure during forming
- Defects like in-plane undulations, wrinkles, thickness reduction and spring-in can occur during the forming process and are governed by the processing parameters and geometry of the tool used during forming
- A list of recommended processing parameters for shaping the laminate off-cuts in single bends is established, which can be used as a baseline for processing the laminate off-cuts into single bends.
- A summary of the processing equipment used for single bend forming is established, which can be used to determine the equipment needed for prototyping or manufacturing of single bends.

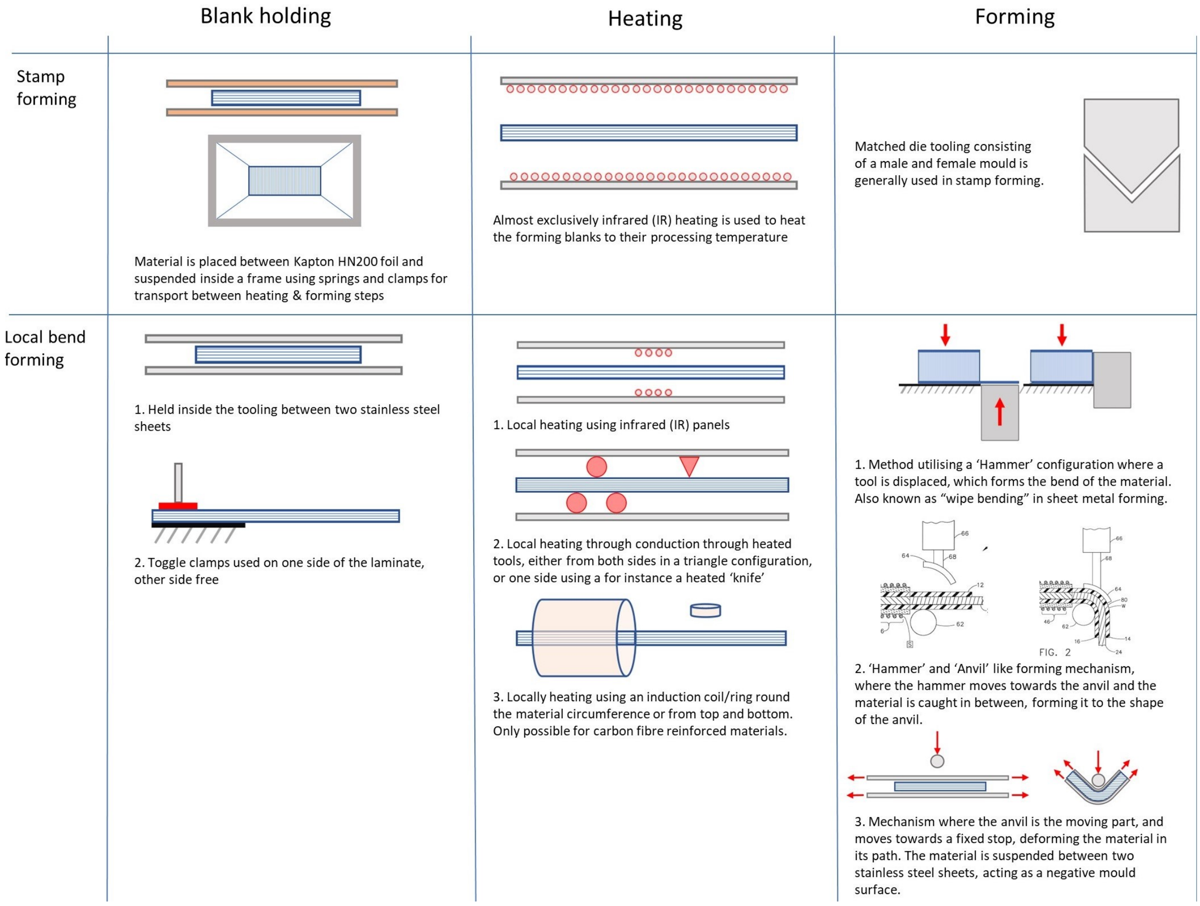


Figure 3.15: Summary of the stamp forming and single bend forming equipment found in literature, company visits and patents

3.4. Local assembly

Next to single bend shaping, local assembly is the other processing method required to create the beam structure out of the laminate off-cuts. Thermoplastic composite materials have a wide range of processes that can be used for joining, including adhesive bonding, mechanical fastening, fusion bonding and dual resin bonding. Within this section, the focus is on adhesive bonding, fusion bonding and mechanical bonding as these are the most convenient options at this point.

3.4.1. Adhesive bonding

Adhesive bonding is a process where a liquid polymer - the adhesive - is placed within the interface of the two to be bonded surfaces, which upon solidification produces a bond. Adhesive joining of thermoplastic composites is difficult due to the low surface energy of the material, which prevents wetting of the adhesive on the surface of the adherend, and prevent the creation of a bond that is strong and durable [12].

To increase the surface energy of the thermoplastic composite material, an additional step of surface treatment can be used which also offers other benefits next to increasing the surface energy of the surface. A surface treatment can also increase the surface area of the bond, by increasing the roughness, and change the surface chemistry to allow for chemical bonds, which are the primary load carrying bonds, and remove any contamination present on the surface [83][84]. Examples of these treatments include plasma treatment, corona discharge,acid etching, silane coupling agents, grit blasting or a kevlar peel ply [85]. Limitations of include the cost of the equipment, difficulty of the surface preparation and restrictions on part sizes [86]. Materials used for structural bonds, with a lap shear strength above 7Mpa, include epoxies, acrylics and urethanes. These adhesives are available in a variety of forms, come either pre-mixed or in separate components and can require different catalysts for curing (or none). It is dependent on the specific application and materials that are being used to determine which of these adhesive types would be suitable [12].

The supplied laminate off-cut material is all of the same polymer type, and have the same outer surface. As such, only type of surface preparation and adhesive has to be determined, which would suffice for the local assembly of all the laminate off-cuts.

3.4.2. Fusion bonding

Fusion bonding is the bonding of two different thermoplastic composite interfaces through a process of fusion, where the interface between the two interfaces becomes diffuse, as illustrated in Figure 2.25. There are four main methods used in the aerospace industry for the fusion bonding of thermoplastic composite materials: conduction welding, resistance welding, ultrasonic welding and induction welding. These four methods make use of different methods to transform the interface of the bond to a melt, to allow for fusion bonding to occur between the respective parts. The equipment used for these methods ranges from relatively simple heat conductors used in conduction welding, to more complex equipment required for induction welding. Pressure also needs to be applied to the substrates during the welding process, to ensure intimate contact for fusion bonding. Main processing parameters of the fusion bonding process include the time to heat the substrate, the applied pressure and the time that the welding takes, which are dependent on the fibre and matrix type of the material, and its geometrical parameters such as the thickness [87] . As there is such a large variety in the thickness of the supplied laminate off-cut material, these parameters will need to be tailored for each specific bond.

The principle, applications and limitations of the four fusion bonding methods are summarised in Table 3.4.

Table 3.4: Summary of the fusion bonding methods used for thermoplastic composite materials [88][87][85][89]

Welding method	Principle	Applications	Limitations
Conduction	Application of heat through conduction at the external surface of the bond interface	- Short cycle times - UD & fabrics - Short & long welds	- Thin laminates - No direct application of heat at interface
Ultrasonic	Creation of friction at the bond interface due to ultrasonic (20khz-40khz) vibrations	- Very short cycle times - UD, fabrics - Short/spot welds	- Long continuous welds - Thickness (max. 3mm)
Induction	Eddy current heating at the interface caused by the application of an external electro-magnetic field	- Medium cycle times - UD, Fabric - Thick laminates	-Radio transparent material interference
Resistance	Joule heating generated at the interface due to the resistance of an electrical conductor	- Short cycle times - UD, Fabric - Long welds	- Conductive materials - Contamination due to electrical conductor - Limited automation possibilities

3.4.3. Mechanical bonding

Joining of thermoplastic composite materials is also possible through mechanical joints using fasteners. Unlike fusion and adhesive bonding, mechanical bonding is reversible, without causing excess damage to the material. Just like with metal parts, fasteners such as bolts, pins and rivets can be used for joining, but some other requirements have to be considered as well.

When using fasteners in a carbon fibre reinforced material, galvanic corrosion is a factor when using aluminium or steel fasteners. To prevent this from occurring, either titanium fasteners can be used, or a material, such as a coating, can be applied between the composite and the fastener to at as a barrier. The design of the fasteners also has to be considered, as to spread compressive load during tightening of the fasteners over the material. If this is not done correctly this can cause cracking of the matrix or fibres, crushing in the case of a sandwich panel and delamination inside the material. The placement of the fasteners compared to the edges of the laminate is also important to consider, as this highly affects the failure mode of the joint. If the ratio of the diameter to the edges of the laminate is chosen incorrectly, premature failure of the joint may occur [12].

Cutting of the holes for joining can be done using drilling or water jet cutting. When drilling the hole it is important to use the correct drill bit, as this can cause delamination or separation of the layers at the beginning or end of the drill bit. Other damage can also occur within the hole during drilling as well, causing fibre pull-out and matrix scratches. Melting of the matrix can also occur during drilling if the temperature increase within the material is too high. Water jet cutting cuts the holes using a stream of water mixes with particles at a very high speed and pressure. This erodes the material away at the location of the hole, both the matrix and the fibres, and does not result in delamination of the part. Limitations of this method include the availability of the machine for processing, and the long processing times [12]

Mechanical fasteners can adapt well to the geometric variety of the laminate off-cuts, as these are designed to account for a variety of thicknesses in the material that they join. To account for galvanic corrosion titanium fasteners can be used, and a maximum diameter of the fastener can be determined by using the minimum width of the laminate off-cuts, and selecting a suitable ratio for this depending on the failure mode. In this way, mechanical fasteners can be used to make reversible bonds between all the supplied laminate off-cuts.

3.4.4. Section takeaways

- Adhesive bonding can be used to make permanent bonds between each the laminate off-cuts, as this is only dependent on the type of matrix used and the surface quality of the material, which is the same for all the laminate off-cuts. For thermoplastic matrices attention has to be paid to the right surface preparation and adhesive due to the low surface energy of the material, which could potentially lead to weak bonds between the parts.
- Fusion bonding can be used to permanently bond the laminate off-cuts to each other, or any other thermoplastic composite material, but require specialised equipment and the processing parameters need to be tailored for each specific bond.
- Mechanical bonding is suitable to create reversible bonds between the laminate off-cuts, as these fasteners can readily adapt to the variety in thickness of the material. Attention has to be paid to material of the fastener to avoid galvanic corrosion, and the size of the fastener relative to the width of the off-cut to prevent premature material failure, and the damage induced in the material during the cutting of the fastener holes.

4
Engineering & Design Dimension

4.1. Introduction

Given the interdisciplinary nature of this thesis project, both the engineering and design dimension of designing a product from laminate off-cuts are explored. This chapter combines the obtained information on the processing, material properties and the context of the laminate off-cuts, and illustrates how these relate to product design. Furthermore, an intent for both the engineering and design dimension is established, each highlighting different aspects of the laminate off-cuts.

4.2. Information overview

When looking at an information structure for product design, information from the material, processing, aesthetics, perception and intent are intertwined and combined to a product [67]. However, wen designing with waste materials, additional information is available on the material context, affecting the processing, aesthetics and properties of the material as well. In Figure 4.1 the information structure for design using the laminate off-cuts is presented, where the additional material context is added.

The information structure when designing with a waste material differs from a 'standard' information structure for product design, mainly due to the added material context of the material being re-used from another application. This context is not just based on material properties, but also captures other factors of the laminate off-cuts such as its defects, quantity, source and geometry, which are more focused on a structure level rather than a material level. These are inherent properties of the material as it comes from its source which provide restrictions or additional opportunities for the design process. They have an effect on the further processing of the material, the material properties and as such also on the intent and final form of the product. The intertwined nature of the information structure is clearly illustrated in this figure, which addresses the need for the addition of the material context when designing using waste materials. As an example, the geometry of the laminate off-cuts affect the ways in which the strips can be processed into a flat plate, and the defects that are present in the material have an effect on the material properties, but also dictate the aesthetic properties of the material.

Within the previous chapters, information is obtained on the processing, material properties and the context of the material, but the intent and final product are still missing. The intent of the product to be designed is formed both through the technical functionality, the product personality and its use.
The technical functionality describes technical requirements that the product needs to adhere to e.g. it needs to provide a certain stiffness, meet a certain regulatory standard or have wheels that are 622mm in diameter. The product personality describes the emotional side of the product - what kind of experience and emotional reaction it wants to evoke from the user.
The personality of a product is formed through its aesthetic properties, where these can be used to create an association, shape the perception of the product and evoke emotions within the user. As an example, a chunky shape with green and desaturated yellow colour, can be used to create an association to the military, which can be perceived as rugged, lasting and functional, and evoking emotions of pride, sadness or happiness. The associations, perceptions and emotions evoked by the user are very dependent on the context, culture and experience of the users, and should be considered in the

design of the product [90].
The use of the product describes the functionality that the product offer to the user, e.g. storing a hot beverage for a mug. This functionality is generally derived from a certain need of the user that is (partially) unfilled, but can also be created through a technological breakthrough that creates a new need for the user.

Within the scope of this project, the focus is put on exploring the opportunities that the laminate off-cuts offer for both the technical functionality and the product personality, through the design of a structural member and a product. A structural member is defined as a load carrying element of a larger assembly, component or product, within the scope of this report. Within the design of the structural member, focus is put on exploring the opportunities that the laminate off-cuts offer for the technical functionality, rather than the product personality. This exploration focuses on the material properties and the processing of the laminate off-cuts, whilst taking the defects, geometry and quantity into account as well. Within the design of a product, the opportunities that the laminate off-cuts offer for both the technical functionality and the technical functionality are explored. This holistic approach makes the exploration more broad, and can explore what opportunities arise from combining the material properties, material context and processing of the laminate off-cuts into a product. The design of the structural member is defined as the engineering dimension, and the design of the product the design dimension.

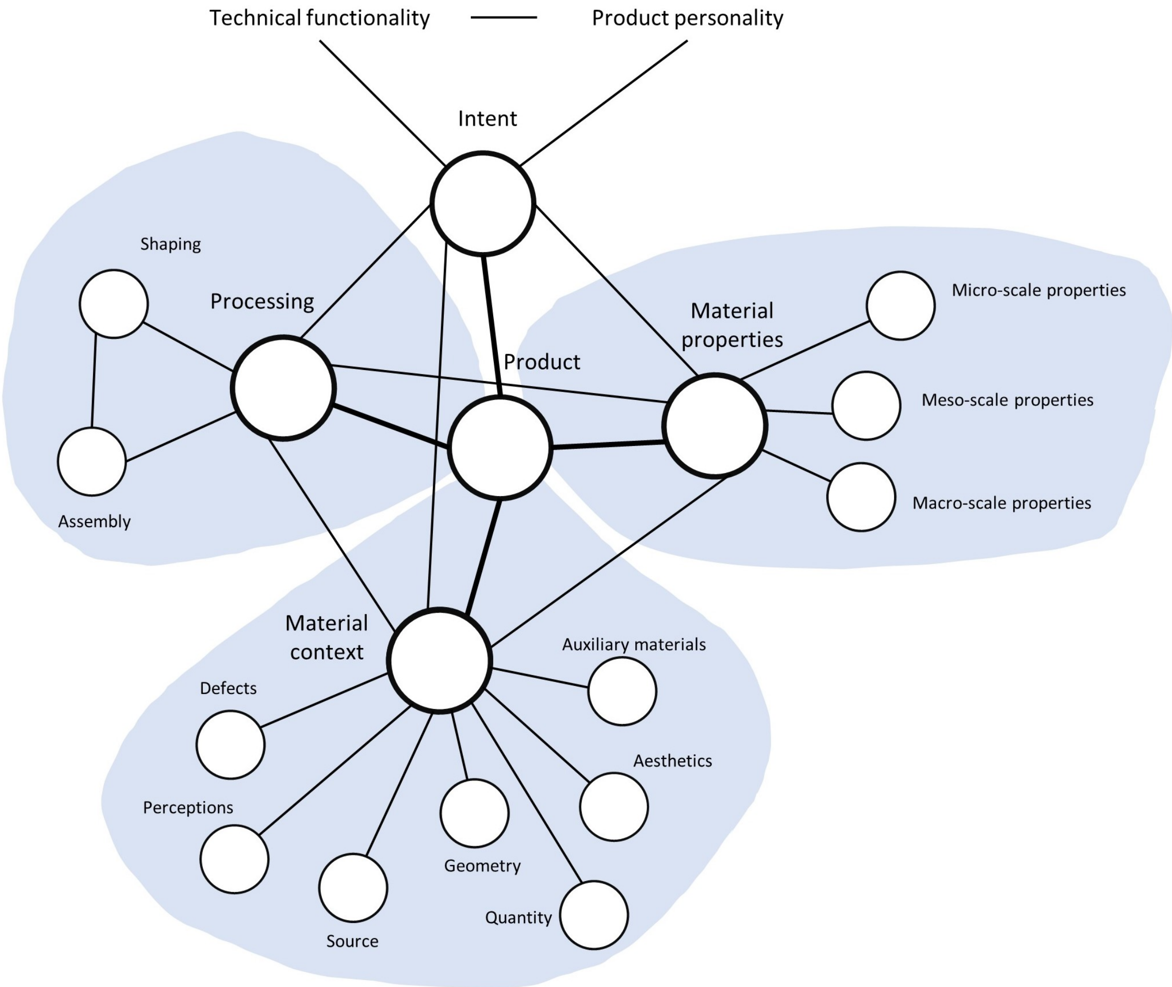


Figure 4.1: Information structure for product design using laminate off-cuts

4.3. Engineering dimension

Within the engineering dimension, the technical functionality that the laminate off-cuts can offer for engineering design are further explored, through the design of a structural member. At this stage it is unknown what the function or intent of this structural member should be exactly, e.g. should it provide a certain stiffness or strength. By using the information obtained from the material context initial criteria for the structural member are derived, to guide the exploration process.

4.3.1. Design criteria

First of all, the structural member should be as adaptable as possible to the variability in the geometry, mechanical properties and defects of the material. If the structure can be easily adapted, a complete redesign of the structural member is not required for every different laminate off-cut, making the implementation of this structural member easier.

Secondly, the manufacturing of the structural member should be as easy as possible using the available tooling at the faculty of Aerospace engineering and Industrial Design Engineering. As the time and resources for this project are limited, it should be possible to explore the manufacturing of the structural member within the timeframe of the project.

The structural performance of the structural member should be maximised in terms of stiffness, strength or weight, to ensure that the laminate off-cuts are not downcycled into lower grade applications. The laminate off-cuts are made from high-performance aerospace materials that offer high specific mechanical properties, high toughness, good chemical resistance and temperature resistance, which should be used to improve the performance of the structure.

Finally, the structural member should be as easy to adapt to new (not the original) functionalities as possible to make re-use in subsequent lifecycles as easy as possible. If the structural member is too tailored to a specific function and application, it will require adapting the structure to this new application, which will required additional resources and limit the scope of possibilities for re-use. Therefore, it would be best if the structural member can be adapted during the design to also fit more generic use cases as well.

With these criteria in mind the exploration of the engineering dimension is started, which is detailed in Chapter 5.

4.4. Design dimension

Within the design dimension, opportunities that the laminate off-cuts offer for creating a product and its personality are further explored. This exploration makes use of the context of the material, as well as its properties and processing. To guide the exploration process, a design vision is created that captures the intent of the to be designed product. The design vision is based on the lack of use of the laminate off-cuts by designers and engineers and the perception that this is a waste material. The intent of the design is to inspire designers and engineers to use the material in their design process, and to demonstrate the value that the material holds. This is captured in the design vision as follows:

> "To **stimulate creative thinking** by designers and engineers about the use of thermoplastic laminate off-cuts, by creating a product that **grabs their attention**, is **relevant** to them and **conveys a strong message about the potential use of the material**."

Design and engineering students are selected as the target group for this project, to bring the material to the attention of a large group and stimulate the use of the material in multiple fields. The focus is put on students, as they will be in a position in the future where they can use the material in their design process. As such, it is valuable to make design students aware of this material early in their career. Furthermore, access to both groups is possible for the final evaluation of the designed product.

4.4.1. Design criteria

The highlighted aspects of the design vision are the criteria to which the final product will be evaluated, and the reasoning behind their selection is further discussed in this subsection.

Firstly, the design of the product should inspire, stimulate creative thinking, designers and engineers to use the material. As there is limited experience in designing products using thermoplastic composite waste materials, the use of the material should provoke curiosity and spark the imagination of the viewers. The material should be used in a novel and creative way, to have designers and engineers start wondering how they could use the laminate off-cuts in their design process. For the to be designed product this means that it should provide enough room for the material to be used in creative and novel way, and not be driven by purely function.

Secondly, the product should be able to convey the message that the laminate off-cuts are not a waste material, but a a valuable resource that can be utilised. The original value of the thermoplastic composite material lies in its properties, allowing for lightweight design in high-end applications. As such, the designed product should make use of the valuable properties of the material, e.g. high mechanical properties, chemical resistance, toughness, or temperature resistance, to create a valuable and functional design. By using it in a valuable and functional application it conveys the message that the material still has value and functionality, and does not have to be downcycled.

Furthermore, the designed product should be relatable for the target group, to ensure that the focus of the target group is on the message that the product conveys, rather than what the product is. This means that the product itself should be familiar for the viewers, and that any expected functionalities of this product are included, to restrict discussion about missing functionalities.

Finally, the product should be able to grab the attention of the target group, and make a lasting impression. This ensures that the message of the product can be conveyed to the designers and engineers. To make the product grab the attention of the viewer it should be interactive, engaging and allow for a close interaction, to lure the target group in for a close interaction with the product and create a personal connection. The product can also be large in size, to ensure that it is easy to see for the target group. Furthermore, it should be unique in appearance, to ensure that it stands out from the context of the product environment.

The final product is also intended to be part of an exposition at the Dutch Design Week, which increases the exposure of the message, and spreads the message of the product beyond design and engineering students. This means that the final product should either be possible to be displayed at the Dutch Design Week, or that a demonstrator of the product should be designed. The demonstrator should be able to be transported to Eindhoven, remain structurally sound during the exposition, and be able to be transported back to Delft.
With the design vision and criteria detailed, the exploration process is started which is further detailed in Chapter 6.

5
Engineering dimension: Beam design

5.1. Introduction

In this chapter the design of a structural member made from thermoplastic laminate off-cuts is further detailed. This process starts with a creative process, where the laminate off-cuts are shaped into intermediate structural forms. This process is detailed in Section 5.2, where one intermediate structural form is selected for further detailing. Through prototyping the variations of the chosen structural from are explored, learning about the different forms and manufacturing aspects of the structure. This process is detailed in Section 5.2.4, where several variations of the structural form are proposed. To be able to use this structural form in a design process, an analytical model is created which is detailed in Section 5.3. This model provides as estimation of the elastic constants of the structural form from its geometrical parameters, allowing for a design tailored to a specific functional requirement. The model is expanded with the failure modes of the structural form, allowing the designer or engineer to design for a specific function or response of the structure. In Section 5.4 the structural form and model for analysis are combined in the final structural member design, where its characteristics and potential applications are detailed.

5.2. Form ideation

In this section the process of creating a new structural form from the laminate off-cuts is detailed. This process started with an ideation session, which resulted in two main ideas. A trade-off was made between these two, and further prototyping was performed with the selected idea. At the end of the section this idea is summarised, and is further detailed in the next section.

5.2.1. Design drawing to discover

The ideation process of the shaping of thermoplastic laminate off-cuts started with a process design drawing to discover, exploring many different options of shaping and attachment of the thermoplastic composite strips into various forms [91]. The aim of this process was to explore how the strips could be made into products or usable shapes directly, or into intermediate construction forms that could be used in subsequent design steps. In this process, the properties or function of the structure are not yet explicitly detailed, to keep the options as wide as possible. The results of this exploration are four different structural forms made by shaping the laminate off-cuts.

The first is the spring-like form, where the thermoplastic composite strips are shaped along a spiral path around a cylinder. This can either be done by curving the strips through the width or the thickness, and curving them along the cylinder. In this way a spring-like structure can be obtained, whose cross-sectional dimensions, which mainly determine the properties of the coil, are dependent on the strip (or a stacked array of strips) that is used within the manufacturing process [92]. This form is shown in Figure 5.1.

The second form is the twisting and bending of a single composite strip into a structural shape. The bending of the strip can be in-plane and out of plane, and the twisting is done along the longitudinal axis of the material. Through twisting of the strip, in-plane bending can be replaced by out-of-plane bending, rotating the cross-sectional properties in the process. These kind of forms are suitable to comply to the contours of a certain shape, like the edge of a seat or the outline of a headrest. In this way they could act as a stiffening element, but also help with the attachment of the internal elements. This form and a possible example application is illustrated in Figure 5.2.

The third form is weaving the strips, through out of plane bending, to create larger intermediate structures. Weaving the laminate off-cuts into a discontinuous structure would allow for the creation of large panels, which can also have curvature. This form is illustrated in Figure 5.3.
One example of a structure that could be made out of this is an outdoor dome frame, as shown in Figure 5.5, where the laminate off-cuts are woven into a double curved shape. Another more structural shape could be a transmission tunnel in a vehicle, as pictured in Figure 5.6, where the laminate off-cuts are shaped into a double curved shape that is also load carrying and an integral part of the structure. Depending on the degree of curvature, the laminate off-cuts could either be elastically bent into place, or stamp formed locally to create the curvature before assembly.
The fourth form is bending of the strips into a corrugated pattern, and assembling these between two strips to create a sandwich structure. This form is illustrated in Figure 5.4. Creating a sandwich beam out of the laminate off-cuts allows for the creation of a long slender beam with variable cross sectional properties over tits length. Furthermore, it makes use of the high strength and stiffness properties of the material of the laminate off-cuts, by loading it compression at the top face, and tension at the bottom face. In this way, stiff, strong, lightweight and height-variable beams can be made using the material, which can be specifically tailored to the requirements.
Variable height beams that need to be stiff, strong and lightweight are used for instance in the construction of a wing, as shown in Figure 5.7. Here the height of the wing-box decreases over its span, requiring a variable height spar beam. Another example is the floor beam of the fuselage in aircraft construction, as shown in Figure 5.8. Here the beam requires an extra height near the edges of the fuselage, possibly due to the loading or attachment, but less at the centre of the beam which is made possible by creating a step in the height of the beam.

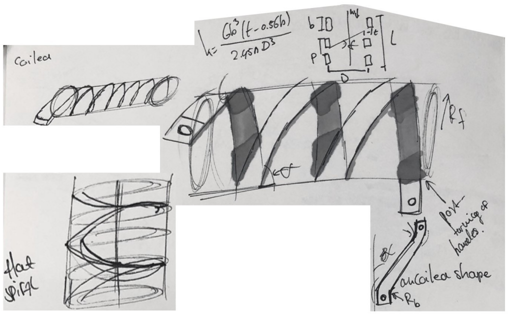


Figure 5.1: Sketches used to explore the in-plane bending and coiling of the strips into coiled spring-like structures

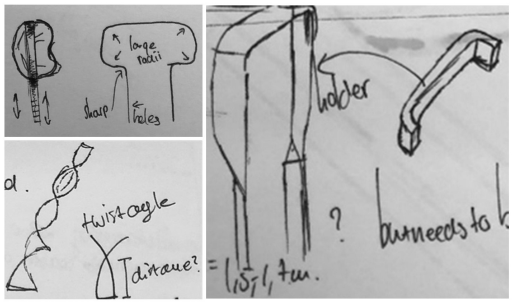


Figure 5.2: Sketches used to explore the twisting and bending of the strips into new structural forms, with a possible application as an outline of a headrest

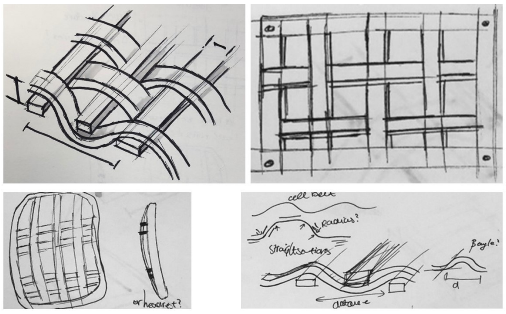


Figure 5.3: Sketches exploring how the strips can be shaped into a woven structure, and its possibilities

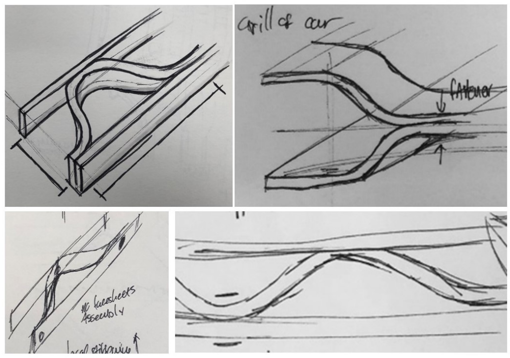


Figure 5.4: Sketches exploring how the strips can be made into a beam-like structure

Figure 5.5: Large double curved domes made through weaving

Figure 5.6: Possible application of a flat sheet, with local bends to comply to a certain form, as a structural element in a vehicle

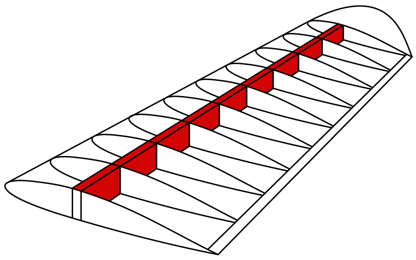


Figure 5.7: Spar beam inside a wing box construction, illustrating a decreasing beam height along the span of the wing

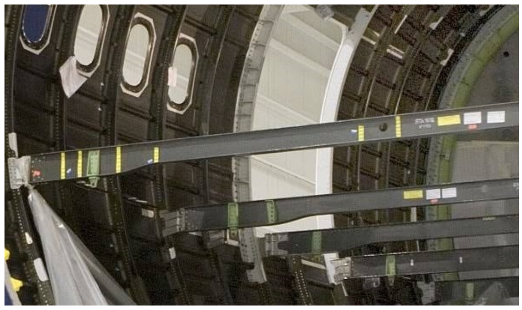


Figure 5.8: Composite floor beam of the Boeing 787 aircraft, demonstrating a step-wise beam height over the length of the beam [93]

5.2.2. Form selection

From these four different forms, one is chose for further study in this project to contain the complexity, and allow for a deeper investigation of how this form can be utilised. This decision is based on the criteria as defined in Section 4.3, which are summarised in Table 5.1. A Harris profile is used to compare how well each of the forms satisfy the criteria, providing a visual indication of which form is the most suitable [91]. This comparison is presented in Figure 5.9, with the reasoning behind the rankings and ratings for each form are detailed in Appendix I.

Table 5.1: Criteria used for the selection of the form of the structural member

Requirement ID	Description
C-FS-1	The form of the structural member should be as easy to adapt to the variable geometry of the strips as possible
C-FS-2	The manufacturing of the form should be as easy as possible using the available equipment at the faculties of IDE and AE of the Delft University of Technology
C-FS-3	The form of the structural member should maximise the structural performance of the structural member
C-FS-4	The structural member should be as adaptable as possible to other functionalities

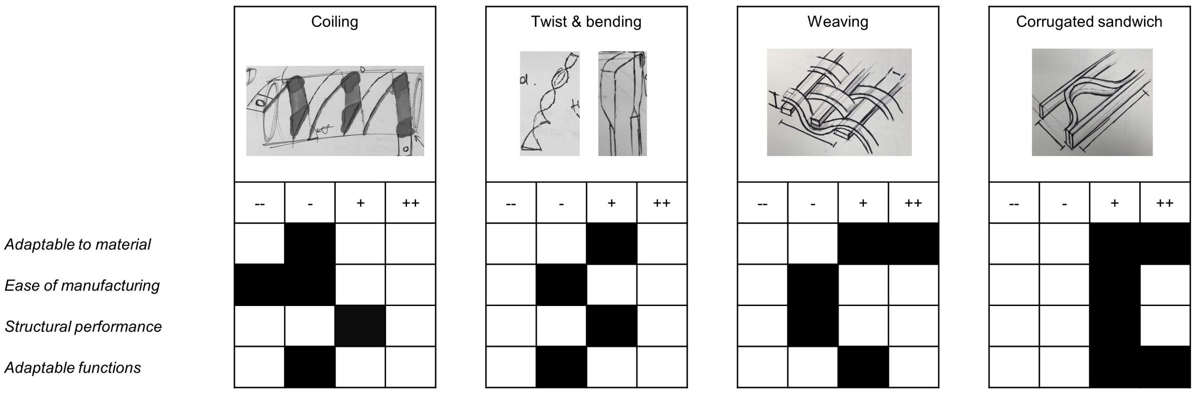


Figure 5.9: Comparison of how well each form meets the criteria using a Harris profile

From the comparison it is observed that the corrugated sandwich form suits the best with the criteria, mainly as this form is easily adaptable to suit the variability in the material, and is easy to manufacture. The structure is easily adaptable to a variation in the geometry of the material, as it offers compensation possibilities in multiple parts of the form. Whereas in the coiling, there is only one option to compensate, and this also limits the design freedom. For the ease of manufacturing, it scores well as it uses commonly available tooling on only a local level of the structure, whereas other methods require more complex tooling or are more difficult to assemble. The shape also allows for placement of the material in the right location to maximise the structural performance of the form, making efficient use of the material. This is where the woven form scores less well, as its intertwined nature results in less efficient material usage. The corrugated sandwich from also allows re-use without requiring much processing as it in the form of standard construction element, although its performance might be dependent on its design. The woven structure can also be re-used in other applications but as this is not in a standard form the scope will be less wide, requiring processing to widen the scope of re-use applications.

5.2.3. Form prototyping

To further explore the shaping possibilities of the laminate off-cuts , prototyping using a representative material is used. By trying to shape the material in the corrugated sandwich form, new opportunities can also be found. In this way the manufacturing of the corrugated beam structure is also tested, which can be used to validate the ease of manufacturing and the processing parameters defined earlier.

The first round of prototyping used cardboard as the material, which was selected as this could be bent by hand and easily attached. In this way the creation of tailored beams is explored, and the manufacturing process is trailed. The process started with marking the locations where the single bends in the corrugation occurred, and placing double sided tape for attachment. Next, the strip was bent at the marked locations and attached, starting from one end. The result of this is shown in Figure 5.10, which was a full scale model using the full lengths of the laminate off-cuts. Prototyping is also explored on a more local scale, as shown in Figure 5.11, where the bending angle of the corrugations, attachment methods and the use of additional stiffening strips in a coiling manner are tested as well. From this it became clear that there were still very many possibilities in the form, and a more representative material might help with narrowing the scope through the manufacturing limit.

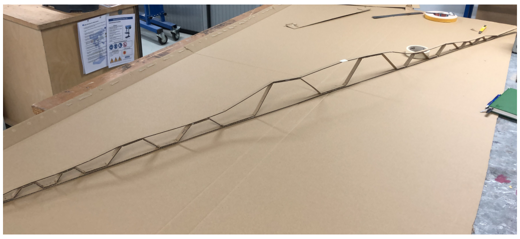


Figure 5.10: Full-scale cardboard prototype corrugated sandwich beam

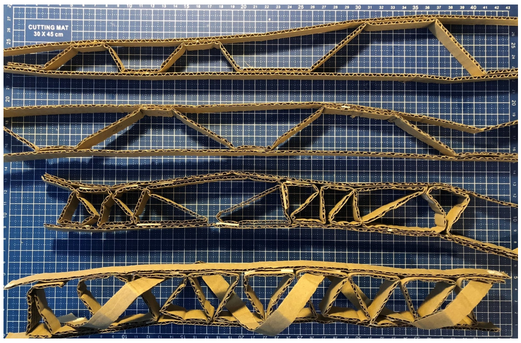


Figure 5.11: Small scale local cardboard variations on the corrugations of the corrugated sandwich beam

In a second round of prototyping the local shaping of the strips into a corrugation is further explored, using PVC strips and an adhesive. The long PVC strips are of similar dimensions, 25mm wide and 2mm thick, and by using heat these can be shaped easily. The goal here was to explore how the shaping of the thermoplastic composite strips would be, and what limitations the process gives to the shape. The PVC prototypes are shown in Figure 5.12. The manufacturing of the PVC prototypes was done using a soldering iron, which could be set to a specified temperature. The PVC strips were held on both sides using small clamps, and pressed onto the metal sheath of the soldering iron, heating the material up locally. After a short period the PVC strip heated up and became flexible, allowing the bend to be made. By repeating this process a few times in a row, a corrugated pattern could be made. This corrugated pattern is then glued, using a PVC adhesive, to both a top layer and a bottom layer to form the sandwich beam structure. An overview of the forming and gluing is shown in Figure 5.12.

One aspect learned from making the prototypes from PVC was that there needs to be a proper way to space the distance between the bends, as this distance also determines the height of the beam. If this distance is not constant, the height of the beam can vary unintentionally, leading to geometric inaccuracies and a possibly unexpected performance. Additionally, the bend angle also needs to be constant for each bend, as this can lead to similar problems. Furthermore, if this bend angle becomes large than 90°, it makes the manufacturing of the bend more difficult as it could hinder accessibility to subsequent bends, this is also shown in Figure 5.13.

Figure 5.12: Two initial forms of the beam sandwich structure made from PVC strips

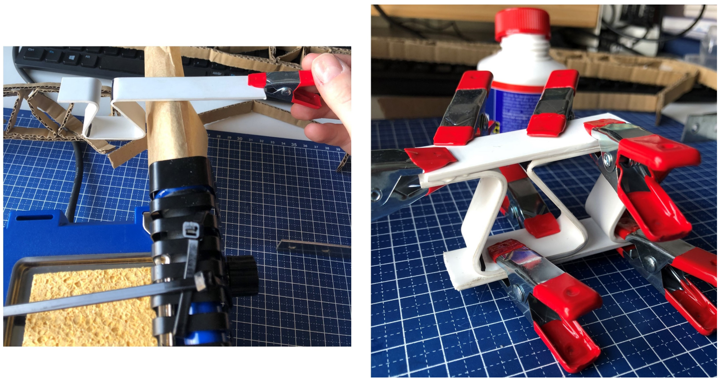


Figure 5.13: left: forming of the PVC strip, right: gluing of the top and bottom strips to the corrugated section

Further prototyping was performed with the laminate off-cuts, to determine a suitable processing method and discover any additional mechanisms that occur when working with a woven thermoplastic composite material instead of just a thermoplastic polymer. A detailed description of the tests performed can be found in Appendix J. The tooling used for the single bend forming test is shown in Figure 5.14, and consists of a manual press with simple steel stock used as the bend forming tooling. The samples are heated through conduction using two large heated steel blocks, and manually placed inside the tooling for pressing into a bend. Two different sample thicknesses are used, which can help determine whether the process would also work for different thicknesses. The material samples used in the single bend test are shown in Figure 5.15.

Overall, the process itself worked well, as the material reached the processing temperature, and could be subsequently formed and cooled in the stock tooling. The conduction heating through the steel blocks also worked with different thicknesses. This test revealed the importance to have a method that accurately tensions and places the material inside the tooling, as this can cause shifting of the material during pressing that results in unwanted defects. Furthermore, the tooling should be tailored to the thickness of the material and the bend to be formed, to keep the pressure distribution even over the surface of the bend.

5.2.4. Structural form variations

From the prototyping it was revealed that the form of the corrugated sandwich beam can still have many varieties. Each of these varieties results in different characteristics of the structure, which can be linked to the loading presented on the structural member. When approached from the loading side of the structure, several different varieties of the structural form can be distinguished, as shown in Figure 5.16

In the case of tensile loading, the frontal area can be increased to lower the stress in the respective top and bottom members. Increasing the beam height has an affect in the case of compressive loading, as this increases the area moment of inertia and increases the critical buckling load. For bending and shear loading, the core leg length and unsupported length at the top of the beam should be reduced, as these are prone to buckling. This can be achieved by adding an additional layer in the middle of the beam, which can also prevent rotation of the corrugations during bending loading [94]. In the case of

Figure 5.14: Tooling used for the experimental forming of single bends in the laminate off-cuts

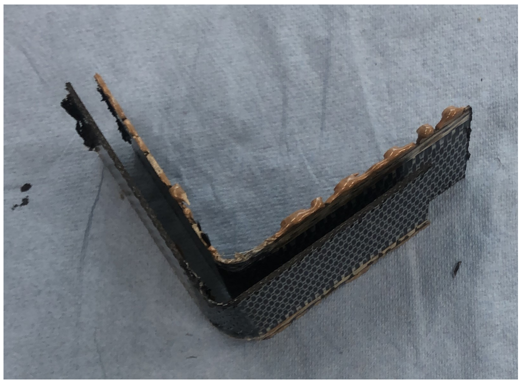


Figure 5.15: Laminate off-cuts formed in a single bend from the experiment

bending, the beam will also be loaded in shear, which can be strengthened by increasing the area at the midpoint of the beam as the shear load will be maximum there. For torsional loading multiple sections can be stacked together in a plus shape to increase the polar moment of inertia, and an additional stiffening element in the direction of the torsional load can be added.

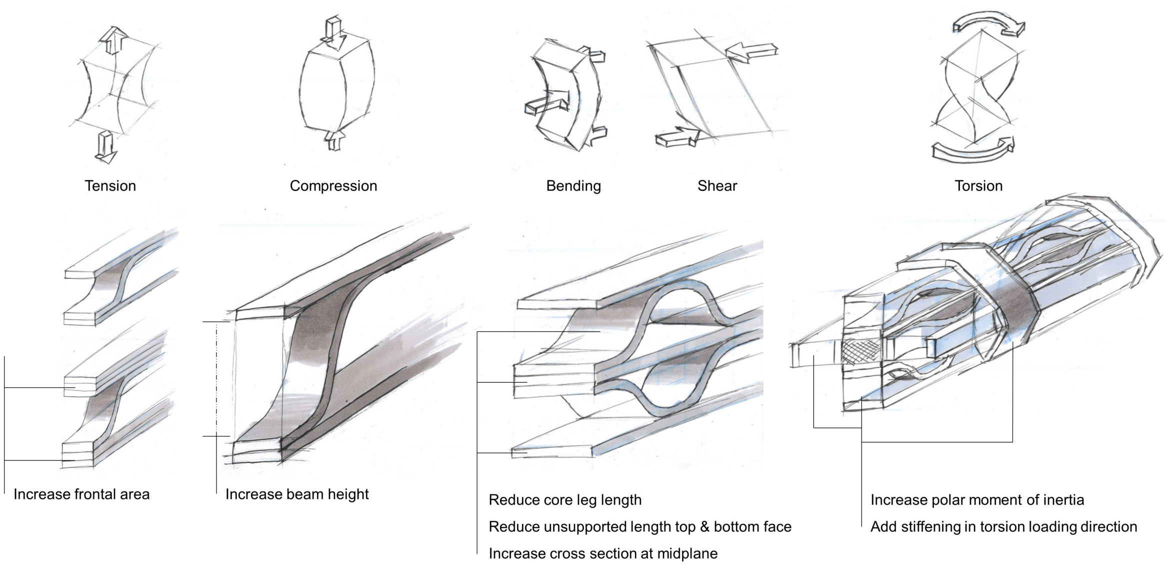


Figure 5.16: Variations of the sandwich beam form adapted for different load cases

5.3. Analytical model

5.3.1. Introduction

To be able to use a corrugated sandwich beam in a design process, it is required to understand how the geometry of the form influences the properties of the sandwich beam, and translate this into simple mathematical relations that the designer can use. In this way the properties of the beam can be tailored through the form, where the function of the beam determines its form. Now that the different variations of the form corresponding to a certain load case, we can tailor the model to capture the behaviour of several of them. The designed model does not include the behaviour of the torsional form, as this is deemed too complex and out of the scope of this study.

The model is based on the geometry of the corrugated section and face sheets, and the properties of the material itself. From this, the equivalent properties of the beam, or a section of the beam, can be determined. The model is expanded with the failure modes of the beam structure under a concentrated bending load, which allows for the tailoring of the design to a specific failure mode.

5.3.2. Beam geometry

The entire beam structure can be simplified and divided into smaller sections, unit cells, for which the elastic constants can be derived. Once these elastic constants are known, the unit cells can be assembled back into a beam structure and used in subsequent analysis. The coordinate system and geometric parameters of the entire beam structure are shown in Figure 5.17, where the beam structure consists of repeating unit cells. The entire beam is divided into unit sections for the analysis, for simplification purposes. The geometrical definitions of the unit cell can be found in Figure 5.18, where the geometric parameters are defined as follows:

- f = half width of the adhesive layer
- p = half period length
- θ = inclination angle of the corrugation pattern
- t_f = thickness of the face sheets
- t_c = thickness of the core material
- h_c = height of the core
- h = height of the beam
- s = length of corrugation leg
- L = length of the beam
- W = width of the beam
- n = number of corrugation unit cells

Some of these parameters can be related through Equation 5.1,Equation 5.2 and Equation 5.3.

$$h_c = h - t_f \tag{5.1}$$

$$b_c = p - 2f \tag{5.2}$$

$$s = \sqrt{h_c^2 + b_c^2} = \frac{h_c}{\sin\theta} = \frac{b_c}{\cos\theta}; \tan\theta = \frac{h_c}{p-2f} \tag{5.3}$$

$$L = n2p \tag{5.4}$$

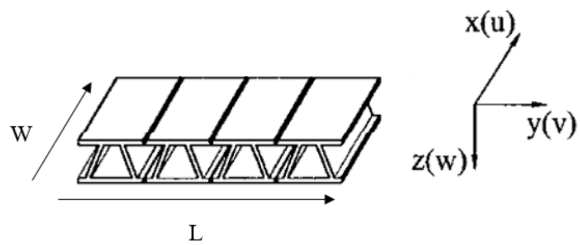


Figure 5.17: Coordinate system and geometrical parameters of the beam [95]

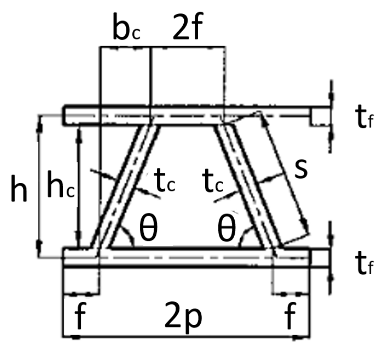


Figure 5.18: Geometry of the unit cell [95]

5.3.3. Elastic constants

Several authors have proposed methods and relations how to determine the elastic constants for a sandwich beam with a corrugated core. In 1951, Libove et al. proposed a method for determining the elastic constants using a detailed derivation the deflection of a corrugated sandwich unit cell. The resulting relations are complex and use many different parameters that require extensive calculations to determine, especially for the transverse shear stiffness. These parameters are also provided for wide range of unit cell geometries in the form of graphs, but are limited to an inclination angle θ of 60° or higher [96]. Further derivation of the transverse shear stiffness of a corrugated sandwich unit cell by Yu et al. and Wang et al. included the effect of an adhesive bond, and demonstrated that the adhesive modulus and thickness have an effect on the transverse shear stiffness [97][98]. These models are highly complex, and allow for the complete modelling of the corrugated section including the radius of curvature used in the bends, but are out of scope for this study. Others have attempted to model the corrugated sections through a homogenisation method or by using energy methods on a single corrugated section, but these methods are either too specific for one type of geometry, do not correlate well with experimental test data, or are based on a geometry that is too far from the envisioned structural form [99][100][101]. Another model is proposed by Lok et al., which includes a simplification for the transverse shear stiffness that makes it possible to use in a design process [95]. This model is limited to f/p ratios of 0.3-0.5, which relates to inclination angles of 45° to 90°. The simplification can be used for unit cells with a inclination angle lower than 45 °, but only in specific circumstances.

This model assumes that the deformation of the panel is small, and that the elastic modulus of the plate in the z-direction is infinite. Furthermore, local buckling of the faces plates is assumed not to occur, and the thickness of the panel remains constant. During deformation of the plate it is assumed that the straight lines normal to the middle plane of the plate remain straight, but not necessarily perpendicular to the middle plane. For the geometry, it is assumed that the face plates are 'thin' compared to the corrugated core plate, and their bending stiffness is also so small it can be ignored. Finally, the stiffness of the core material is taken into account in the x-direction, but not in the y-direction.

The coordinate system and sign convention for the elastic properties of the unit cell are shown in Figure 5.19, where D_x and D_y describe the bending stiffness in the x- and y-direction, D_{xy} describes the twisting stiffness, and D_{Qx} and D_{Qy} describe the transverse shear stiffness in the x- and y-direction respectively.

The bending stiffness in the x- and y-direction are described by Equation 5.5 and Equation 5.6 respec-

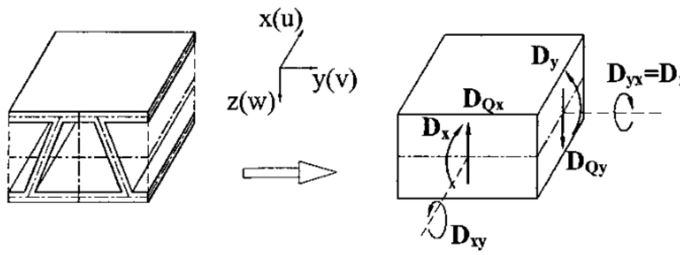


Figure 5.19: Sign convention for the stiffness parameters of the unit cell of the corrugated sandwich panel

tively, where E is the elastic modulus of the thermoplastic composite material, I_f and I_c are the area moment of inertia of the face sheets and cores for bending about the neutral axis in the yz-plane per unit length as described by Equation 5.7 and Equation 5.8 , I_{xz} is the area moment of inertia in the xz plane as described by Equation 5.9, and v is the Poisson ratio .

$$D_x = E\left(I_c + I_f\right) \tag{5.5}$$

$$D_y = \frac{EI_{xz}}{1 - (\frac{v^2 I_c}{I_c + I_f})} \tag{5.6}$$

$$I_f = t_f h^2 \tag{5.7}$$

$$I_c = \frac{t_c h_c^3}{12p\sin\theta} \tag{5.8}$$

$$I_{xz} = \frac{W t_f^3}{6} + \frac{W t_f h^2}{2} \tag{5.9}$$

The relation for the shear stiffness in the x-direction is given by Equation 5.10, where G is the shear stiffness of the material.

$$D_{Qx} = G t_c \frac{\frac{h^2 t}{p s t_c} + \frac{1}{6}\left(\frac{h_c}{p}\right)^2}{\frac{t}{t_c} + \frac{s h_c}{3ph}} \tag{5.10}$$

The simplified relation for the shear stiffness in the y-direction is given by Equation 5.11, where J and J_C are the moment of inertia of the face plate and core about their neutral axis in the xz-plane given by Equation 5.12[95].

$$\begin{aligned} D_{Qy} = \frac{E t_f L}{1-v^2} &\left(\left(\frac{f}{p}\right)^2 \left[\left(\frac{f}{p}\right)^3 + \left(1-\frac{f}{p}\right)^3 + \frac{J}{J_c}\frac{s}{2p}\left(1-\frac{2f}{p}\right)^3\right]\right. \\ &\left/ \left\{\left(\frac{2f}{p}\right)^3\left(1-\frac{f}{p}\right)^3 + \frac{J}{J_c}\frac{s}{p}\left[\left(\frac{f}{p}\right)^3\left(2-\frac{t}{d}-\frac{2f}{p}\right)^2 + \left(1-\frac{f}{p}\right)^3\left(\frac{t}{d}-\frac{2f}{p}\right)^2\right]\right\}\right. \end{aligned} \tag{5.11}$$

$$J = \frac{W t_f^3}{12} \tag{5.12}$$

$$J_c = \frac{W t_c^3}{12} \tag{5.13}$$

The twisting stiffness of the unit cell is described by Equation 5.14.

$$D_{xy} = 2 G I_f \tag{5.14}$$

These units of stiffness can be normalised to elastic constants of an equivalent 2D-orthotropic place continuum through the relations provided [102]:

$$E_x = \frac{12 D_x}{h_f^3} \tag{5.15}$$

$$E_y = \frac{12 D_y}{h_f^3} \tag{5.16}$$

$$G_{xy} = \frac{6 D_{xy}}{h_f^3} \tag{5.17}$$

$$v_{xy} = v_x \quad v_{yx} = v_y \tag{5.18}$$

$$G_{xz} = \frac{D_{Qx}}{k_s h_f} \tag{5.19}$$

$$G_{yz} = \frac{D_{Qy}}{k_s h_f} \tag{5.20}$$

$$\tag{5.21}$$

Where k_s is the shear correction factor which varies from 5-6.

These elastic constants are valid for only one geometry of unit cell, and can be used for the analysis of a whole beam when the geometry remains constant. If the geometry changes over its length, the elastic properties of the unit cell also change which will result in different elastic properties. In this case, the beam can be discretized into multiple unit sections into a compound beam, where each section has

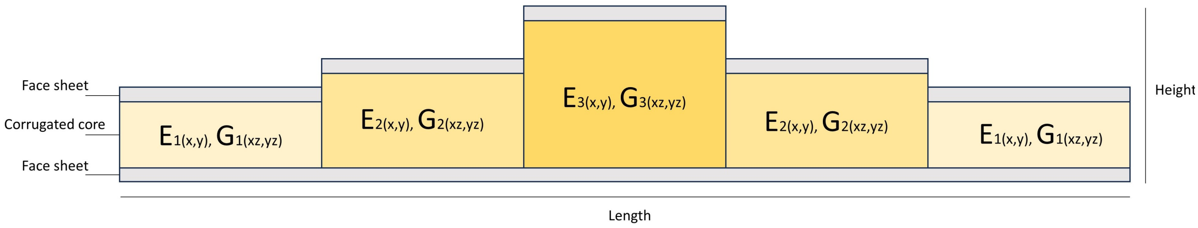


Figure 5.20: Discretized model of a variable height corrugated sandwich beam

different elastic constants, as shown in Figure 5.20.

The unit cell elements can also be stacked in height, as shown in Figure 5.16 for the bending and shear variation, which allows for additional freedom in the design of tailored beams. The effect on the elastic properties vary with the degree of stacking, and the unit cell properties of the stacked elements. For the bending stiffness, the additional components of the stacked units have to be taken into account in Equation 5.9, where the total height of the beam has the largest effect on this value. For the shear stiffness of the beam, the contribution of each stacked core element is taken into account separately and combined in the total stiffness of the beam element. The shear deformation of a beam with a degree of stacking of 2 under a shear load is shown in Figure 5.21, illustrating the contribution of each stacked unit cell. The shear stiffness of a sandwich beam is defined as the product of the shear modulus multiplied with the area, as shown in Equation 5.22[103]. For stacked beams the contribution to the shear stiffness of each element can be described by Equation 5.23, and can be assembled to form the shear stiffness of the beam as shown in Equation 5.24.

$$S = W h_c\, G \tag{5.22}$$
$$S_n = w * h_{cn}\, G_n \tag{5.23}$$
$$S_b = S_1 + S_2 = W h_{c1}\, G_1 + W h_{c2}\, G_2 \tag{5.24}$$
$$\tag{5.25}$$

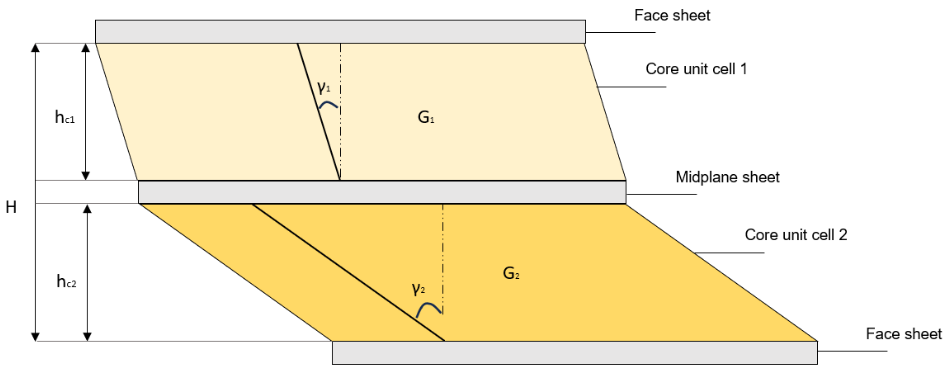


Figure 5.21: Shear deformation of a stacked core sandwich beam (m=2)

5.3.4. Failure modes

The modes in which the structure can exhibit significant changes in its mechanical performance are described by the failure modes. In this case, the failure modes for a beam under a vertical concentrated load in the centre of the beam are analysed. Within the sandwich beam there are three main components that can fail: the face sheets, the core material and the adhesive (if the sections are connected with an adhesive). These failure modes for these three components are summarised in Figure 5.22. For the face sheets and corrugated core the most important material and geometric properties in the design are the compressive strength, the elastic modulus and the thickness. The first two are properties of the thermoplastic composite material and can be found in Table 2.8. The thickness of the material is a variable, and can be chosen according to the range of available laminate off-cut thicknesses.

To determine at which load each of the failure modes occur, it is necessary to determine the loads on the respective elements during bending. During bending, it is assumed that the bending moment is carried by the face sheets, and that the shear load is carried by the corrugated core and adhesive layer. This is a common assumption for sandwich panels under bending, as the core material generally has a low bending stiffness and the face sheets provide little shear stiffness [103] . With this defined, the compressive load on the face sheet can be determined from the bending moment, and the load on the core and adhesive from the shear load. For this analysis, a unit section at the middle of the beam is considered as this is the most highly loaded unit cell of a beam structure under bending.

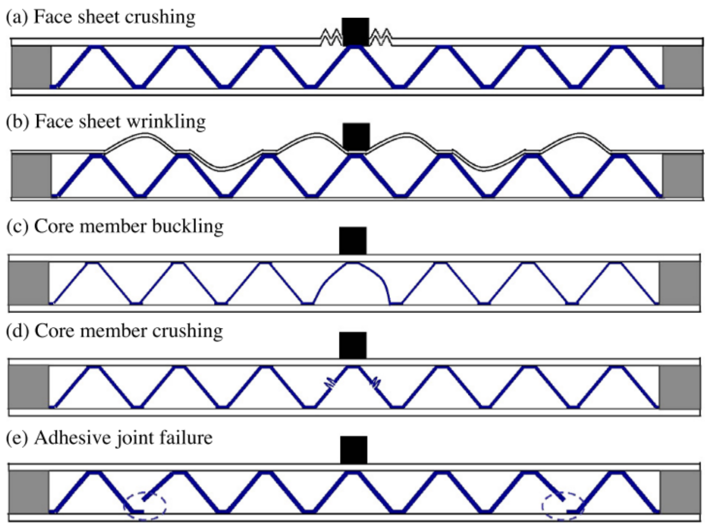


Figure 5.22: Summary of the failure modes considered in the failure prediction [101]

To determine the compressive stress in the face sheets, we can use beam theory applied to a sandwich structure. This describes the stress of of the face for a given height h in Equation 5.26, where I_{xz} is described in Equation 5.9. When combining these and setting for the maximum height of the sandwich beam we obtain Equation 5.27 [103].

$$\sigma_f = \frac{M}{I_{xz}} z \quad \text{where:} \quad \left(\frac{h}{2} - \frac{t_f}{2} \leq z \leq \frac{h}{2} + \frac{t_f}{2} \right) \tag{5.26}$$

$$\sigma_{fmax} = M \frac{\frac{h}{2} + \frac{t_f}{2}}{\frac{W t_f^3}{6} + \frac{W t_f h^2}{2}} \tag{5.27}$$

Where the maximum moment is described by Equation 5.28[104]

$$M = \frac{PL}{4} \tag{5.28}$$

Resulting in Equation 5.29, when combining Equation 5.28 andEquation 5.27.

$$\sigma_{fmax} = \frac{PL}{4} \frac{\frac{h}{2} + \frac{t_f}{2}}{\frac{W t_f^3}{6} + \frac{W t_f h^2}{2}} \tag{5.29}$$

For the core and the adhesive layer, the normal stress is determined through decomposition of the shear force into two components: the normal force in the corrugation legs and a horizontal shear force. A similar approach has been followed by Lu et al, and Li et al. for corrugated prismatic cores [105][106]. It is assumed here that the corrugation legs can only support a normal force, the adhesive only a horizontal force, that there is no rotation of the leg, one end of the leg is pinned and the other end can only move in the z-direction. A schematic of this is shown in Figure 5.23, from which the normal force in the corrugation legs and a horizontal force in the adhesive are derived in Equation 5.30 by using static equilibrium. As a sanity check, it means that at a low angle θ the normal force in the leg will be very high to compensate for the load P, resulting in a high load in the adhesive. When θ nears 90°, the normal force in the leg is equal to half of the applied load P, and the load on the adhesive is low.

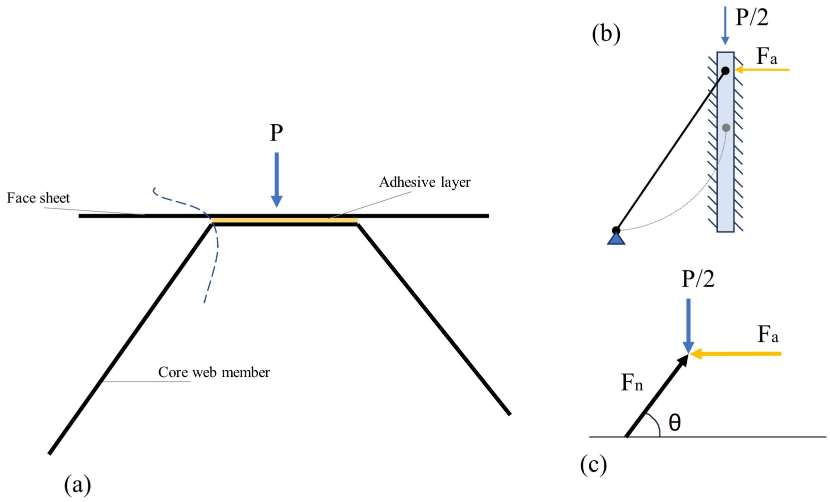


Figure 5.23: a) cut-section of the global loading condition, b) simplification and boundary conditions on the core leg members, c) Force decomposition overview

$$F_n = \frac{P}{2\sin\theta} \tag{5.30}$$
$$F_a = \cos\theta F_n \tag{5.31}$$

The normal stress in the corrugation leg can be derived by dividing over the area of the leg, and the shear force by dividing over the bonding area (fW, see figure Figure 5.17), which are given in Equation 5.32 and Equation 5.33.

$$\sigma_c = \frac{F_n}{t_c W} = \frac{P}{2\sin\theta t_c W} \tag{5.32}$$
$$\tau_a = \frac{F_a}{fW} = \frac{\cos\theta P}{2\sin\theta fW} \tag{5.33}$$

1. **Face crushing**

Face crushing is describes the failure of the top plate under a compressive load. This failure mode is reached when the compressive stress in the top face sheets reaches the compressive strength of the material. The compressive strength is maximum at the maximum height of the beam (the most outer ply of the laminate), as described by Equation 5.27. Rewriting Equation 5.27 for the compressive strength, Equation 5.34 is obtained, where where σ_{cmax} is the compressive strength of the material as given in Table 2.8.

$$\sigma_{cmax} = \frac{PL}{4}\frac{\frac{h}{2}+\frac{t_f}{2}}{\frac{Wt_f^3}{6}+\frac{Wt_fh^2}{2}} \tag{5.34}$$

Rewriting this to isolate for the applied force, Equation 5.35 is obtained.

$$P_{FC} = \sigma_{cmax}\frac{4}{L}\frac{\frac{Wt_f^3}{6}+\frac{Wt_fh^2}{2}}{\frac{h}{2}+\frac{t_f}{2}} \tag{5.35}$$

2. **Face wrinkling**

Face wrinkling is the buckling of the face sheet across the length of the corrugated section. To estimate the wrinkling load, the suspended section is regarded as a simply supported wide plate that is loaded in compression from the supported sides, and free on the other edges [107]. It is required that the dimensions width (W) and unsupported length ($2p-2f$) do not differ by more than an order of magnitude. The critical buckling stress for a simply supported plate with free edges is given in Equation 5.36:

$$\sigma_{cr} = \frac{\pi^2}{12}\left(\frac{W}{2p-2f}\right)^2\left(\frac{E}{1-v^2}\right)\left(\frac{t}{W}\right)^2 \tag{5.36}$$

When equating this to the maximum normal stress in the face members Equation 5.37, is obtained. when rewriting for the applied load P, Equation 5.38 is obtained.

$$\frac{PL}{4}\frac{\frac{h}{2}+\frac{t_f}{2}}{\frac{Wt_f^3}{6}+\frac{Wt_fh^2}{2}} = \frac{\pi^2}{12}\left(\frac{W}{2p-2f}\right)^2\left(\frac{E}{1-v^2}\right)\left(\frac{t}{W}\right)^2 \tag{5.37}$$

$$P_{FW} = \frac{4}{L}\frac{\frac{Wt_f^3}{6}+\frac{Wt_fh^2}{2}}{\frac{h}{2}+\frac{t_f}{2}}\frac{\pi^2}{12}\left(\frac{W}{2p-2f}\right)^2\left(\frac{E}{1-v^2}\right)\left(\frac{t}{W}\right)^2 \tag{5.38}$$

3. **Core member buckling**

For the core members the same procedure can be used, only the length of the core member leg (s), as given in Equation 5.3, is now the unsupported length. As such, the critical stress for buckling in the core members is given in Equation 5.39.

$$\sigma_{cr} = \frac{\pi^2}{12}\left(\frac{W}{s}\right)^2\left(\frac{E}{1-v^2}\right)\left(\frac{t}{W}\right)^2 \tag{5.39}$$

relating this to the normal stress in the core member Equation 5.40 is obtained, and when rewriting for the applied load Equation 5.41 is obtained.

$$\frac{P}{2\sin\theta t_c W} = \frac{\pi^2}{12}\left(\frac{W}{s}\right)^2\left(\frac{E}{1-v^2}\right)\left(\frac{t}{W}\right)^2 \tag{5.40}$$

$$P_{CMW} = \frac{\pi^2 2\sin\theta t_c W}{12}\left(\frac{W}{s}\right)^2\left(\frac{E}{1-v^2}\right)\left(\frac{t}{W}\right)^2 \tag{5.41}$$

4. **Core member crushing**

The crushing of the core members is determined by dividing the normal force on the members by the area of the core members, and setting this equal to the maximum compressive strength of the material. By using Equation 5.32, and the maximum compressive stress of the material, Equation 5.42 is obtained. It is assumed here that the stress over the cross section of the core members is constant.

$$\sigma_{cmax} = \frac{P}{2\sin\theta t_c W} \tag{5.42}$$

$$\tag{5.43}$$

When rewriting for the applied load P, Equation 5.44 is obtained.

$$P_{CMC} = \frac{\sigma_{cmax}}{2\sin\theta t_c W} \tag{5.44}$$

$$\tag{5.45}$$

5. **Adhesive bond failure**

The adhesive joint fails when the maximum shear stress in the adhesive is reached. For an adhesive this stress value is given, and is dependent on the quality of the bond. As such, the maximum stress in Equation 5.33 can be replaced by this value resulting in Equation 5.46. When rewriting for the applied load, Equation 5.47 is obtained.

$$\tau_{max} = \frac{\cos\theta P}{4\sin\theta f W} \tag{5.46}$$

$$P_{ABF} = \frac{\tau_{max} 4\sin\theta f W}{\cos\theta} \tag{5.47}$$

5.4. Final structural member design

In this section the results of the previous sections are combined into the final design of the structural member, summarising the form of the structure, the manufacturing of the structure and the options for design using the model. From this, suggestions for possible applications for the structural element are proposed.

5.4.1. Form

The form of the corrugated sandwich beam structure is summarised in Figure 5.24. The features of the form include the possibility of using a variable geometry of the top and bottom face sheet, and a corrugated strip that can vary in height and length as a core. In this way, the cross sectional properties of the beam can be tailored along its length, without requiring an excess of material. In this way the material can be placed where it offers maximum benefit, allowing for a material efficient design. Furthermore, as the shape is in a generic

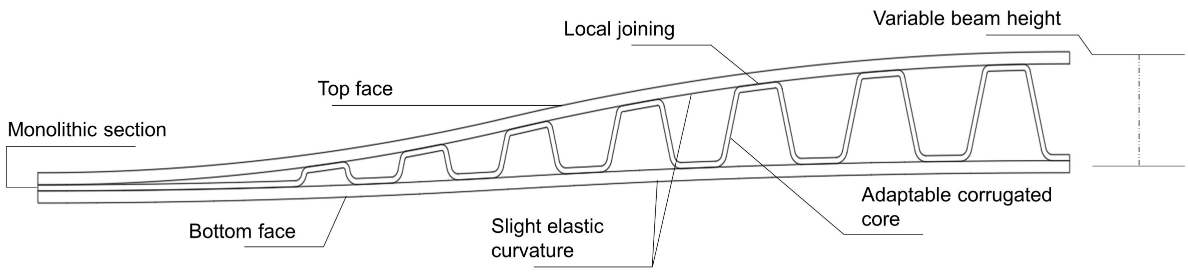


Figure 5.24: Summary of the features of the corrugated sandwich beam structural member

5.4.2. Manufacturing

The manufacturing of the corrugated core can be done using a press and a non-isothermal production process, as demonstrated in Figure 5.25. Within this production process conduction elements can be used to locally heat the laminate off-cut, and a guiding system that controls the placement of the laminate off-cut into the press is required. The moulds need to be tailored to the thickness of the material and the geometry of the bend, in order to ensure an even pressure distribution over the surface of the bend. When the corrugated core has been shaped, the top and bottom face sheets can be locally attached using an adhesive at the flat locations of the corrugated core, as shown in Figure 5.26.

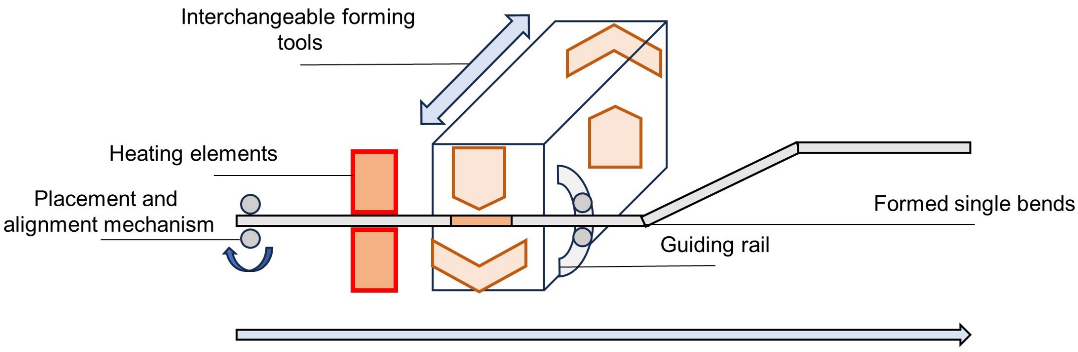


Figure 5.25: Proposed manufacturing process for the corrugated core of the corrugated core sandwich beam

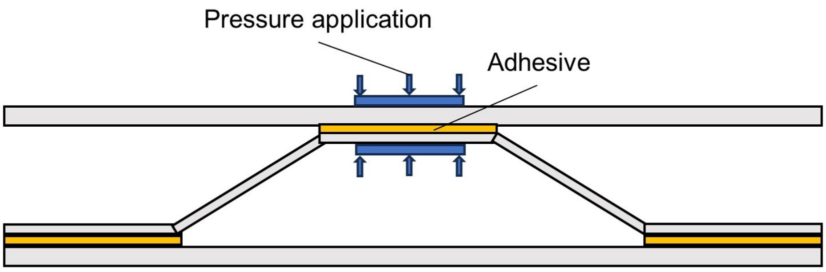


Figure 5.26: Local assembly of the corrugated core to the face sheets of the corrugated sandwich beam using adhesive bonding with an external applied pressure

5.4.3. Modelling

The analytical model made for the corrugated sandwich beam allows the designer to obtain the equivalent properties of the beam at a given location of the beam, and allows for an estimation of the failure mode from the geometry of the corrugated core and face sheets. The model uses a simplified mathematical expression to obtain the equivalent properties of the corrugated core, making it possible to implement in a design process. In this way the designers can tailor the design of the beam at any given location, and adapt it to a certain failure more. Such a process is illustrated in Figure 5.27, demonstrating the function of the model in a design process.

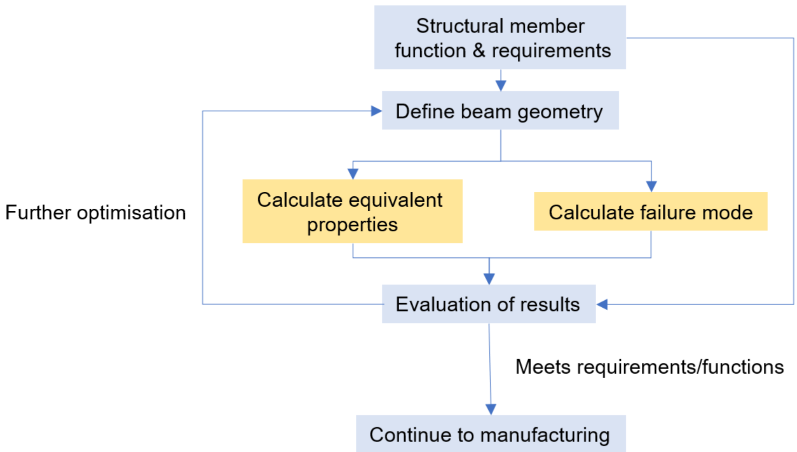
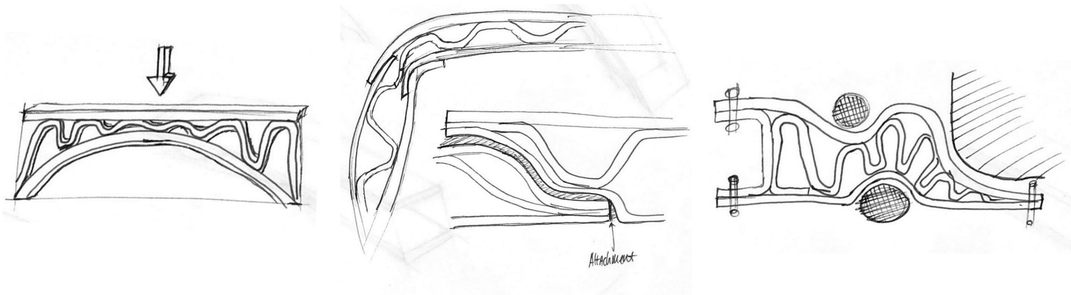


Figure 5.27: The analytical model (in yellow) allows for an iterative design process of the corrugated sandwich structure

5.4.4. Design opportunities

With the results of the previous sections, several applications of the corrugated sandwich beam structure are proposed. This is done by targeting a specific functionality of the structure, and exploring where these might be useful. Functionalities of the corrugated sandwich beam structure include the ability to tailor the geometry along the beam length, as shown in Figure 5.24, or a predetermined bucking response.

Tailoring the geometry of a beam along its length allows for the varying of the properties along its length, the creation of integrated beam designs and beams through complex spaced. Varying the geometry along the length can increase or decrease the stiffness of a beam along its length, resulting in an efficient beam design. In cases where the curvature of the entire beam is slight, the corrugated core is the only elements that has to be tailored to this application, as the face sheets can be elastically bent into shape. The beams can also have integrated attachment methods, allowing for the creation of larger tailored structures. This gives the designer the freedom to design larger structures out of multiple beam elements that are each tailored to their specific application. In other cases when the geometry is restricted or complex, both the face sheets and the core material can be thermoformed suit the application. These example cases are illustrated in Figure 5.28. By varying the geometry of



a) b) c)

Figure 5.28: a) Height optimised beam for bending, b) Assembly of multiple tailored beams with integrated attachment points, c) complex beam geometry within restrictive boundary conditions

the face sheets and the corrugated core, the structure can be designed for a specific response. This can give additional functionality to the structure and gives the designers and engineers additional design freedom. The structure could be designed specifically for buckling at a given load, as illustrated in Figure 5.29. This gives the designer the freedom to design for a linear elastic behaviour until a certain load, and a post-buckling response of the structure after this load. The post-buckling response could allow the structure to deform more than what would be possible within the linear elastic regime, and without compressive failure of the material. This would be for instance of value for structure that need to be stiff until a certain load, and allow for large deformation afterwards. Examples of where these kind of structures can provide value are wing-morphing structure, allowing it to be stiff until a certain load, but flexible once a load threshold is passed [108][109]. An example of this is shown in Figure 5.30.

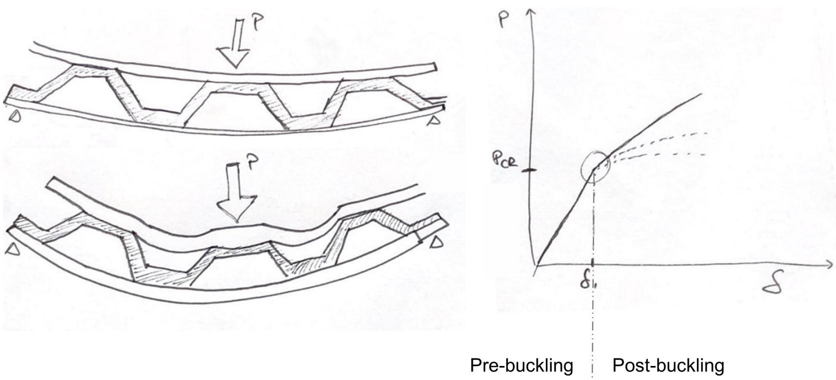


Figure 5.29: Example of the response of a beam that is designed for buckling

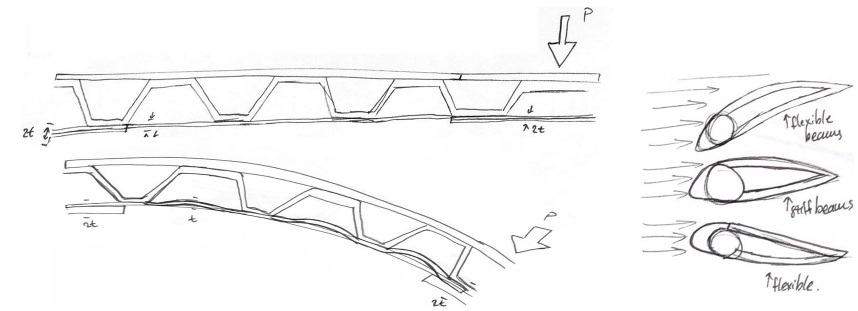


Figure 5.30: Example application of a beam that is designed for buckling in a flexible wing design

6
Design dimension: Bridge design

6.1. Introduction

In this chapter the design dimension of a product made from laminate off-cuts is further explored. The starting point of this exploration is the design vision, and the criteria defined for the final product. From the design vision, the product should grab the attention of the user/viewer, be relevant to them and convey a strong message about the use of the material. Furthermore, the product is envisioned to be part of an exposition at the Dutch Design Week to broaden the reach of the message of the product.

The design process starts with an ideation process, utilising tools such as mind mapping, group brainstorming and design drawing to discover to generate a large quantity of ideas [91]. This ideation process is detailed in Section 6.2. The large number of ideas is narrowed down by checking whether these address the criteria in a table, and a finer selection of the remaining ideas is done using a Harris profile. This selection is presented in Section 6.3, and the final selected idea is used as input for the further development into a concept. The concept development starts with an exploration of the structure and design styles of the idea, and is followed with more detailed conceptual design of the formal aspects of the idea. This part of the concept development is described in Section 6.4. From this more detailed exploration, a final concept is created which is presented in Section 6.4. The concept is embodied further by manufacturing prototype versions of the components of the bridge concept. This embodiment process is described in Section 6.5, and concludes with a render of the embodied bridge design, and a manufacturing plan for each component.

6.2. Ideation

The ideation process was performed in multiple rounds, where each round explored ideas that were closer related to the design vision than the previous round. The results of each of the ideation sessions can be found in Appendix K

The ideation process started with an exploration of products centred around bending and torsion, using a mind map. From this several industries were targeted, including sports equipment, outdoor furniture and indoor furniture.

The second round of ideation was performed in a group setting, using a process of brainstorming. The ideation used a method of imagination to set the scope for the idea generation: ”How would you use this material if it was infinitely strong?”. The opposite of this question was also tried and another focusing on the adaptability of the material. From this many ideas were generated that were clustered into groups and presented as single ideas.

The third round of ideation put the aesthetic, material and perception aspects of the material as the leading elements, and focused on exploring products or objects that could highlight these aspects. For this round of ideation, it was imagined that generated ideas would be placed on the pedestal in the water near the faculty of Industrial Design Engineering, which is close to the main access path of the Delft University of Technology campus. This pedestal is shown in Figure 6.1 and Figure 6.2. The aspects highlighted by these ideas include delivering a positive value, the conductive nature of the material, the uniqueness of the material and the durability of the material. These ideas are show in Figure 6.3, Figure 6.4, Figure 6.5 and Figure 6.6.

For the fourth round of ideation the target audience of the product was further detailed and focused on connecting these groups through a common ground. The idea generation used a process of design drawing to discover, where a common ground was envisioned and everything related to this common ground was visualised.

Figure 6.1: View of the pedestal in the small pond near the faculty of Industrial Design Engineering, with the main access road in the back

Figure 6.2: View of the pedestal from the main access road of the campus with the faculty of Industrial Design Engineering in the back, and the access bridge on the left

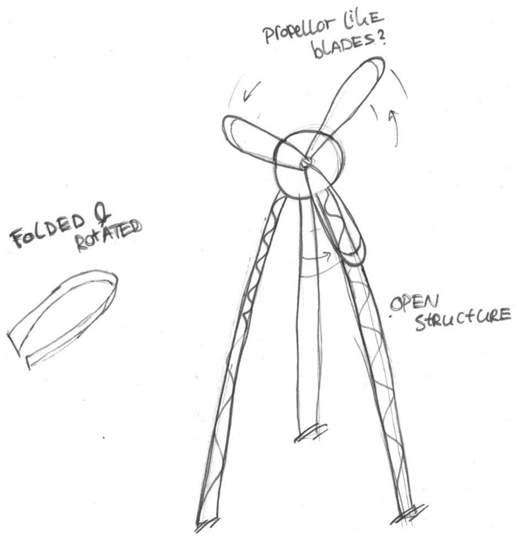


Figure 6.3: Windmill idea that demonstrates a positive value creation, a high-tech environment, futuristic appearance and acts as a symbol of sustainability

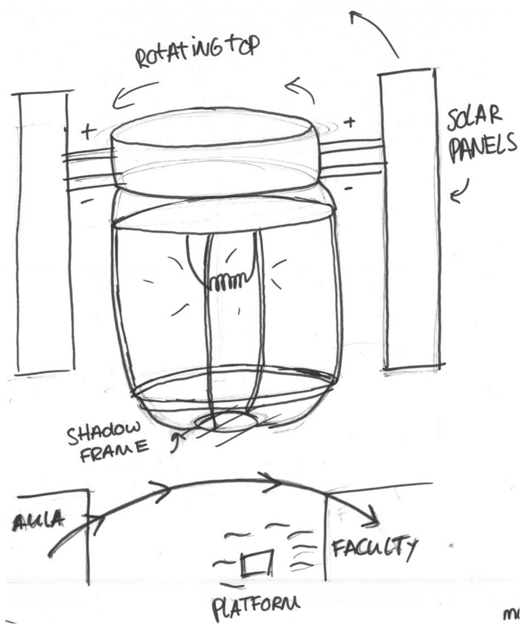


Figure 6.4: Lamp idea that demonstrates the conductive nature of the carbon fibres, highlight the reflection of the material through the solar panels and has a contrasting old lamp appearance

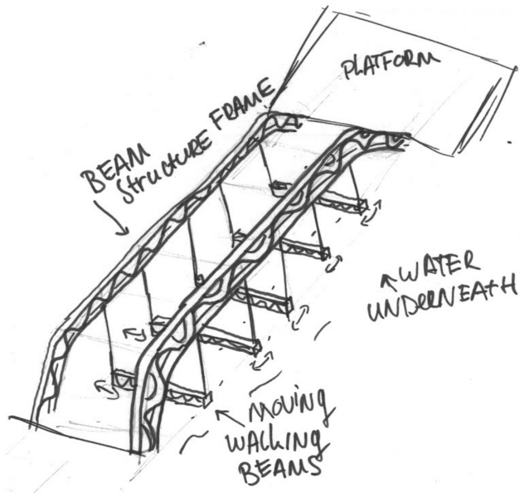


Figure 6.5: Bridge idea that is inviting to the user to try, allowing them to experience it closely, and highlights the mechanical properties and durability of the material

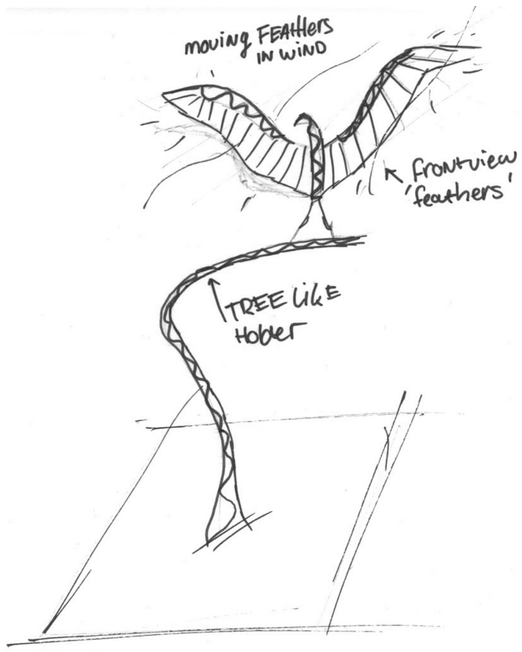


Figure 6.6: Bird idea that relates to the origin of mastering flight with aircraft, that highlights the uniqueness of each laminate off-cut, and demonstrates the reflection and movement of the material in the wind

6.3. Idea selection

The selection of an idea is performed according to the design vision. The criteria used for the selection are how well the product would allow for the creative and novel use of the material, how valuable and functional the design would be, how familiar the products would be for the user and how interactive and engaging the product would be. The first step is that all the ideas from a single ideation round are ranked whether they meet or do not meet the criteria, as is presented in Table 6.1, with the most important criteria at the top, and the least importat at the bottom of the table.

For the first ideation round, the product ideas are centred around the function of the product, which

Table 6.1: Summary of the evaluation of the ideation rounds to the selection criteria

Criteria	Ideation round 1	Ideation round 2	Ideation round 3	Ideation round 4
Allow for creative and novel material use	x	✓	✓	x
Valuable and functional use of material	✓	x	✓	x
Familiar product	✓	x	x	✓
Interactive	x	✓	x	✓
Engaging	x	x	✓	✓

gives less room for novel and creative material usage. The ideas do use the value and function of the material in the product function, and are also familiar to the target group. However, the ideas are not overly interactive, and engaging. The ideas from the second round allow for a creative and novel use of the material, but do not really use the value and functionality of the material in their functionality. The ideas presented are also not too familiar, and which might cloud the message of the material. The products were interactive, but their interaction is not engaging enough to lure the target group in. The ideas from the third round do allow for a creative and novel use of the material as their structure is not purely function driven, and they each make different use of the value of the material in the function of the product. However, utilising the value of the material in the product function and allowing for a creative and novel way of using the material makes the ideas less familiar as product, which can cloud the message of the material. As these products will be placed on a pedestal in the water, their interaction with the target group will be minimal, but they are designed to be engaging enough to make the target group stop walking and look over. The fourth round of ideation resulted in ideas that are familiar for the target group, interactive and engaging to use, as these are tailored to a common ground of the target group. They could capture the attention of the target group but were not able to effectively communicate the value of the material through the product forms, and provide limited options for novel and creative material use.

As a result, the ideas from the third round of ideation are selected for further selection, as the opportunity to use the material in novel and creative ways and how the product utilises and communicates the value of the material is the most important. The second round of idea selection uses a Harris profile to evaluate the four ideas from the third ideation round on the same criteria, and make a final selection. The Harris profile used for the selection is presented in Figure 6.7, and the details on the different levels of the criteria and the reasoning behind the selection can be found in Appendix L.

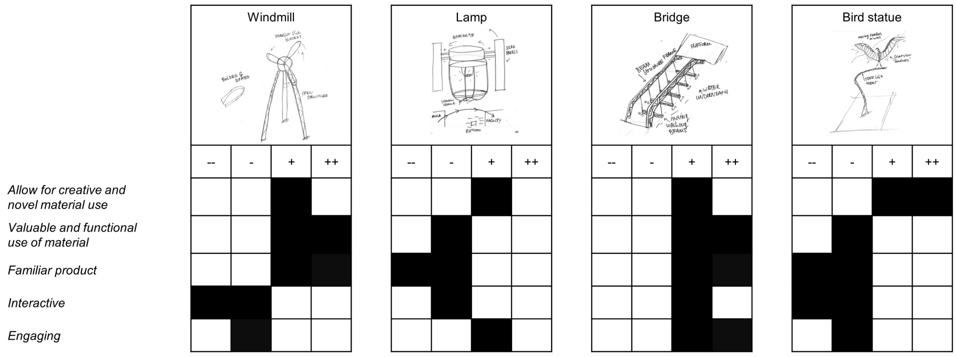


Figure 6.7: Harris profile used for the evaluation of the ideas according to the criteria

From this comparison, it is clear that the bridge idea fulfils the criteria the best out of the four ideas. It offers ample room for the laminate off-cuts to be used in a novel and creative way, through its structural members and aesthetic elements. It also utilises the mechanical properties, and aesthetic properties of the material and is used to enhance the performance of the product, making functional use of the material. Furthermore, as bridges are common in the public space, it will be familiar to the target group, and it offers a possibility for a close interaction through touching and walking upon. It is here that the close match to the windmill idea is broken, as the windmill would not offer much opportunity for interaction. Even if the windmill was placed on a patch of grass, where people could get close to it, it would still not offer many interaction opportunities. Furthermore, the bridge does can make people turn their head and lure them into an interaction, where the others would not offer this.

The four ideas were also presented in a Circular Design Lab meeting at the Industrial Design Engineering faculty, to gauge the interest of the design students regarding these four ideas. Most of the reactions of the students were positive towards the bridge idea, and mentioned that they would for sure try to use the bridge to the platform, just to try it out. This confirmed the interactive and engaging nature of the bridge idea. Combining both the results of the Harris profile and the interest of the design students, the choice was made to continue with the bridge idea in the concept development.

6.4. Concept development

The concept development started with an exploration into the types of bridge structures, with the aim of learning how the loads in these types are distributed and for which spans these are suitable. After this, five different design styles are explored that can be used to highlight aspects of the laminate off-cuts, detailing their origin, and their characteristics. The results of this exploration are processed into an envisioned design structure and style for the bridge, and a collage is made to visualise this. The development continues by detailing the formal aspects of the bridge with the context of the bridge as a starting point. From this, the proportions and scale of the bridge are determined. To detail the form and shape of the bride, design drawing to discover is used to explore several forms, which are translated to the shape and form of the bridge. The use of the bridge by the target group is covered by detailing the ergonomics and interaction, detailing which additional features are required and their dimensions. How and with which materials the bridge comes together is covered in the materials and materialization, where a each element of the bridge is further detailed. At the end of this section, a final conceptual design is presented that incorporates the results of each of these formal aspects.

6.4.1. Bridge structure

There are six main types of bridge structures: beam, truss, arch, cantilever, cable stayed and suspension. Each of these bridge structures has a different method carrying the load that is presented on the bridge, consisting of the load passing over the bridge (passengers, cars, trucks, trains etc.), and its own weight [110][111]. This exploration covers the load carrying mechanism of the bridge, the complexity of the construction and design, and the span that can be covered with each type. This information is used to make a selection which type of bridge structure would be suitable to use for the design of the bridge from the laminate off-cuts.

Within a beam bridge, the load is carried by a structural beam element that supports the deck of the bridge. This beam element is loaded in bending, causing the top to be loaded in compression and the bottom in tension. The construction and design of beam bridges is relatively simple, as the deck and the load carrying elements can be integrated into one structural element for analysis and construction. A beam bridge is suitable for covering relatively small spans to spans of 120m, where the cross section of the beam can be increased to increase the stiffness and reduce stresses, or pillars can be used along its length to reduce the length of the beam sections, for covering longer spans [112].

For longer spans than beam bridges, a truss structure bridge can be used. A truss structure bridge consists of members that are arranged in a triangular pattern, where the members are loaded either in compression or tension. The top members of the bridge are loaded in compression and the bottom in tension, where the arrangement of the diagonal members decides how these are loaded. The construction and analysis of truss bridges is relatively complex, due to the number of structural elements and connections between these that need to be analysed. Truss type bridges can be used to cover spans ranging from 9 - 180m, depending on the geometric scheme of the truss used [112].

Arch bridges feature a curved load bearing element that supports the deck of the bridge. Arch bridges require abutments at the beginning and end of the bridge, which resist the arch weight and vertical loads in the horizontal direction. Arch bridges can be relatively simple or complex in their construction, depending on whether the load bearing arch member is a single unit, like in modern arch bridge construction, or made out of smaller elements, such as bridges built in the roman era. As this load bearing member is only loaded in compression, the geometry and materials used in the construction can be specifically designed to carry this load, allowing for large spans to be realised [113].

A cantilever bridge is based on two opposing cantilever elements, supported only on one side, that are connected at their ends. These elements can consist of simple beam elements for small spans using high-stiffness and strength materials, or be in the form of truss structures. The cantilever bridge usually consists of three sections, with two high supports along its length and a suspended section between these two, making the construction of these bridges relatively complex. These high supports allow for the tensile and compressive loads of the suspended section to be carries to the foundation of the bridge, allowing large spans to be covered.

For spanning longer ranges than truss or arch bridges, cable stayed bridge construction can be used. A cable stayed bridge has a similar configuration as a cantilever bride, with three spans and two vertical supports. The vertical load on the main deck between the two supports is carried by cables connected to the two main supports, which means that this element can span a large length. These cables are loaded in tension, which result in a compressive load on the main supports and the deck elements. There are some bending moments on the supports and the deck elements, but their contribution to the overall loading is considered small compared to the axial loads [114]. The construction and design of these types of bridges is relatively complex, due to the amount of load carrying member and their interaction to carry the load.

Suspension bridges allow for the largest span to be covered compared to all other bridge types. Suspension bridges utilise the same structural layout as cable stayed bridges, with three spans and two supports with a large main suspension cables spanning between the two supports. These two main suspension cables are much thicker than the cables in a cable stayed bridge and are made from high tensile strength materials. From these two (or more) main suspension cables smaller cables run down and suspend the deck. These cables are all loaded in tension, and transfer this load in compression to the supports, and need to be supported from the start and end of the bridges by abutments [115]. The construction of these bridges is complex, mainly due to the number of load carring member and their interaction to carry the load.

An overview of these different bridge types and the loading present on their structural elements is presented in Figure 6.8.

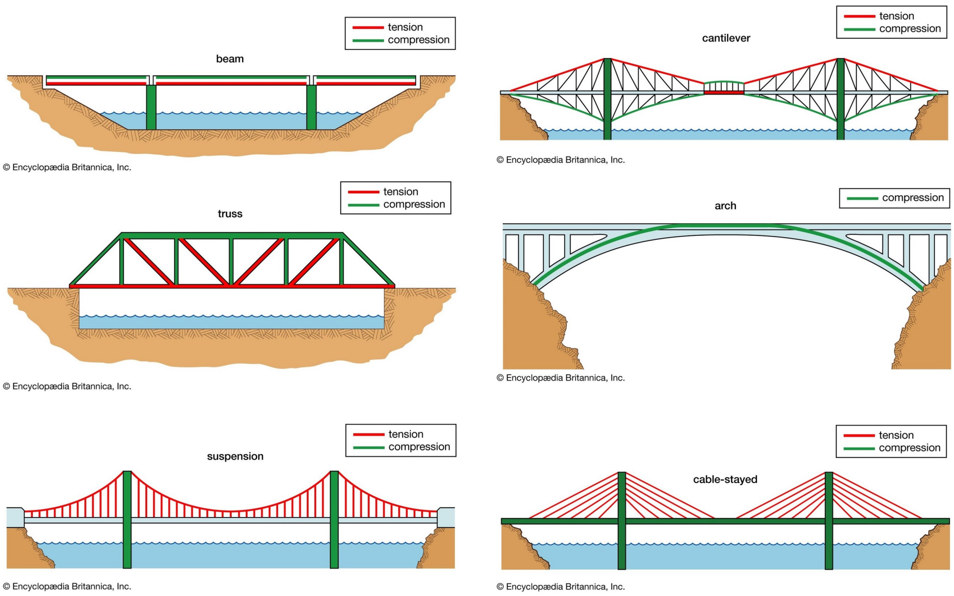


Figure 6.8: Overview of the different bridge structures with the type of loading on their structural elements [116]

6.4.2. Design styles

Next to to the structural style of the bridge, a a style for its formal aspects can also be explored. This exploration starts with a selection of styles from the field of architecture and design, taking the aesthetics and perception of the laminate off-cuts as a basis. These key characteristics for these designs styles are compiled and examples in the form of products or architectural elements are presented. This exploration is used in the design process to form a new design style based on the characteristics of the laminate off-cuts.

A classical architectural style can be used to contradict the futuristic and modern perception of the material. This design style finds its origins within the ancient Greek later the Roman architecture, ranging from the 7th century BC to 14 CE. This architectural style is characterised by the use of columns with specific orders and ornate detailing, which was later expanded to include arches and walls due to material and building innovations by the Romans. Other characteristics include symmetrical and spatial arrangements of the structural elements, and the varying of the proportions of these. The materials used in construction include stone, brick and concrete [117]. An example of the classical Roman architecture is presented in Figure 6.9.

The Art Deco architectural style is a design style that captures the excitement and glamour of the modern age, and can be used to highlight the modern and exclusive nature of the laminate off-cuts. The design style originated in 1925 at the Exposition Internationale des Ats Decoratifs et Industriels Modernes in Paris, and was developed further in the next decade. The style is characterised by demonstrating speed and movement, either through the form or the construction. Other aspects include the use of geometric forms, in contrast to organic and flowing forms used in Art Nouveau, and the use of glamour through decorative motifs elements to impress or attract attention [117]. An example of the use of the Art Deco architectural style is presented in Figure 6.10.

The high-tech architectural style incorporates the high-tech nature of the industry and construction into the design, and can be used to highlight the high-tech nature and origin of the laminate off-cuts. The style has been used in early form from 1935, but came forward in 1977 with the construction of the Centre Georges Pompidou. The style can be seen as the ultimate extent of the precept form follows function, where the form of the design is purely driven by its function, or as being completely anti-form where form is a by-product of the materialization. The style is characterised as having a industrial aesthetic that exposes the construction, with structural and functional elements of the design becoming part of the aesthetic [117]. An example of a high-tech application is shown in Figure 6.11.

Minimalism as a design style is used to described the stripping away of any expressive elements of a design, resulting in clean, elegant and functional design, which can be used to highlight the functionality of the laminate off-cuts. Minimalist design became well known since the early 1960's, due to exhibitions by American artists, but has also been present in much older design works where simplicity and functionality were of importance. Minimalist design features include sleek lines and a clean appearance that is free of ornamentation, with a focus on functionality and simplicity. The use of different materials is limited as much as possible, to preserve the simplicity of the design, where each material is carefully chosen for its functionality [118]. An example of a minimalist design is shown in Figure 6.12.

Streamlining as a design style is focused on creating a form of least resistance through a medium like water or air, and can be used to refer back to the industry in which the laminate off-cuts find their origin: the aerospace industry. These streamlined forms can indicate a sense of speed, efficiency and progress, which relate back to the original function of the material in the Aerospace industry. Streamlining in design was present from the late 1920's until the second world war, where it was applied to cars, trains and ships, but also to products such as vacuum cleaners and radio's. Streamlined design is characterised by rounded edges, smooth surfaces and low horizontal profiles. The forms have no clear boundaries but are absorbed by each other, and feature limited external details. The curves follow organic forms, and are contrasting to angular geometries [119]. An example of a product designed in the streamlined style is presented in Figure 6.13.

From these styles, a collage is created with the envisioned style for the bridge, which is presented in Figure 6.14.

Figure 6.9: Pont du Gare aqueduct in France built by the ancient Romans in the first century BE [120]

Figure 6.10: Elements of the Art-Deco style on the Golden Gate Bridge, demonstrating the geometric forms as decorative elements [121]

Figure 6.11: High-tech architecture used in the design of the Centre Pompidou building in the centre of Paris [122]

Figure 6.12: Thonet no.18 chair designed by Michael Thonet in 1859, demonstrating minimalist design ia chair [123]

Figure 6.13: Electrolux model 30 vacuum cleaner designed in 1937 illustrating a streamlined design [124]

6.4.3. Envisioned bridge structure and style

The criteria used for the selection of the bridge structure include the complexity in design and the complexity in construction. As there is limited time for this project, both the complexity in design and construction of the bridge structure needs to be low, to allow for a detailed design and the construction of a demonstrator. Furthermore, this would allow for a sharper focus on the message that is to be conveyed by the bridge, which is another important aspect of the design. As such, the beam structure is chosen for the bridge, as this has the least complexity of all the bridge types, and is also suitable to cover a short distance.

The design style for the bridge is a mix of all the design styles that are explored in the previous section. For the shape and form of the bridge, it is envisioned that this links back to the origin of the material, the aerospace industry, through the use of streamlined and sleek lines within the construction. The bridge should become the Airbus of bridges, capturing its aerodynamic shape and efficient design. Furthermore, the aesthetic of the material will be used to attract attention to the design, highlighting its exclusivity and futuristic nature. As the bridge will be located outside, the reflections of the sun onto the material, as shown in Figure 2.49, will increase the aesthetic interest of the material. The amount of decorative elements will be minimal, to keep the focus on the message to be conveyed by the bridge design, and maintain the efficiency of the bridge. To highlight the role of the material in the structure, the structural elements are to become part of the aesthetic of the bridge, and visible to the viewers. These elements of the design style are captured in a collage, as presented in Figure 6.14.

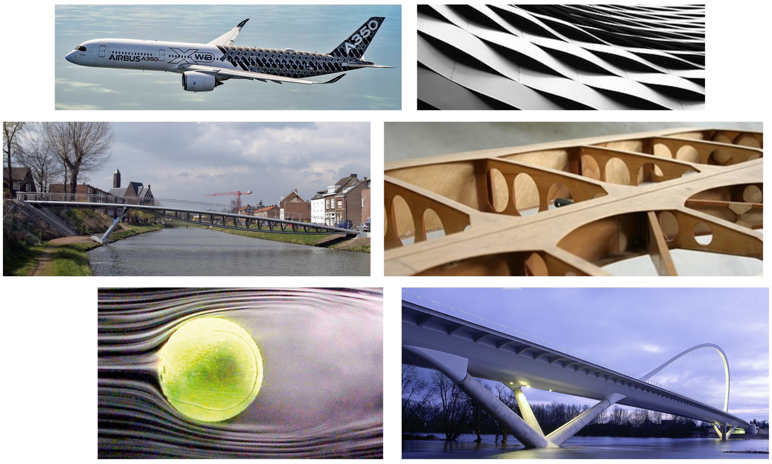


Figure 6.14: Collage capturing the envisioned bridge structure and design style

6.4.4. Shape and form

The shape and form of the bridge detail on one end the more functional aspects of the bridge, e.g. the slope that the pedestrians will walk on, but also creates a part of the personality of the bridge, e.g a streamlined bridge. Following from the design style of the bridge, it is foreseen that the main outline and design of the bridge will use streamlined and sleek line. Using the airfoil of an aircraft as inspiration, the outline of a bridge with streamlined and sleek lines is explored, as show in Figure 6.15. It is envisioned here that the pedestrians passing over the bridge become a part of the airflow, through which the airfoil shape cuts. As such, two possible paths of the pedestrians are envisioned, one passing along the top of the airfoil and one passing below the airfoil. An a-symmetric shape is used to refer to the air foil shape, and to create a sense of direction. The web of the bridge, the space that is between the top and bottom path, alludes to the design of an aircraft rib, highlights the asymmetry of the bridge and demonstrates the shaping of the material. An exploration of different types of web forms is presented in Figure 6.16.

A second idea for the shape and form was also explored, which revolved around the use of cables to support the deck, like a suspension or cable stayed bridge. This idea was discontinued due to the added complexity of the structural form, and as it is less suited to cover such a relatively short distance.

This idea can be found in Appendix M.

As a result, an initial shape and form of the bridge is created, that features an a-symmetrical streamlined shape representing an airfoil to symbolise speed and movement, two pedestrian lanes to immerse the pedestrians as a part of the flow and a web structure between the lanes that allows for a visible structure and alludes to the design of an aircraft rib. This design is presented in Figure 6.17.

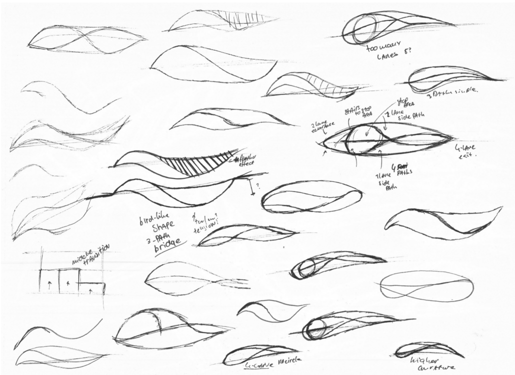


Figure 6.15: Form study exploring streamlined forms that can be used as a pedestrian or cyclist bridge with multiple lanes

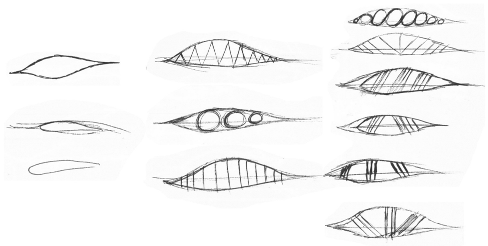


Figure 6.16: Explored variations of the bridge web structure

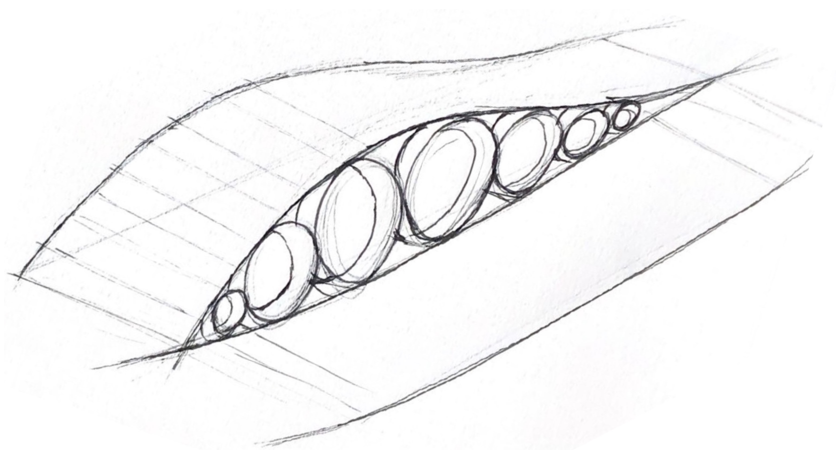


Figure 6.17: Initial shape and form of the bridge, illustrating the two lanes of the bridge, the aerodynamic a-symmetric shape and the web structure

6.4.5. Bridge context

By studying where the bridge will be placed ad what the further context of this area is, several initial requirements for the bridge can be determined to which the shape and form can be adapted. The aim of the bridge was to allow access to the small pedestal in the pond in front of the faculty of Industrial Design Engineering. The distance from the embankment to the pond can be measured from satellite images from Google Maps, and shown that this is around 17.5m or 15m, depending on which side the pedestal is approached. The dimensions of the pedestal can be obtained in a similar manner and show that these are 2x2m. The area that the bridge is placed at is a pedestrian area, where no cyclists are allowed. As such, it can be expected that the bridge will mainly be used by pedestrians, and no other types of passengers. An overview of the physical context is shown in Figure 6.18.

As such, the bridge should have a width not larger than 2.0m, as this would exceed the width of the pedestal, have a length ranging from 15-17.5m, and be tailored for pedestrian use.

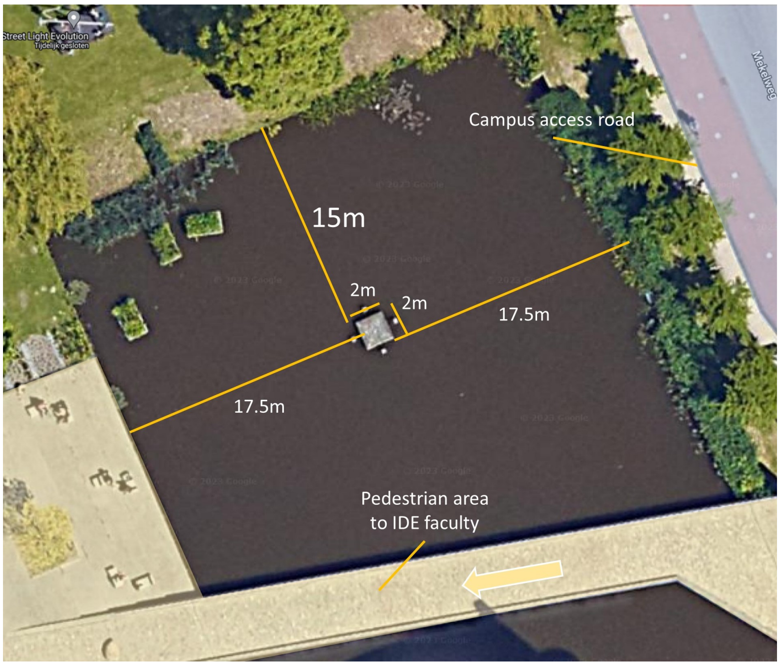


Figure 6.18: Dimensions of the pond, pedestal and length required to get there, with the pedestrian area and campus access road indicated

6.4.6. Ergonomics and user interaction

With the target user group of the bridge known, a further look can be taken at more specific requirements for the geometry, loading and functional elements of the bridge. For this investigation a design guide for pedestrian and cyclist bridges is used [125].
From this design guide, is is determined that the minimum width of a passenger lane of the bridge should be 1.2m, to allow the pedestrians to pass each other when walking in opposite directions. Furthermore, it shows that this thin section can be maximum 20m long, possibly because this small width can cause a slow flow of pedestrians across the length. These measurements are shown in Figure 6.19. Additionally to the width requirement, it also states that a railing is required when the drop from the bridge is more than 1.0m. This railing should have a minimum height of 1.0m, and should not allow for spheres with a diameter larger than 0.5m to pass through. These measurements are shown in Figure 6.20 .

As a result, the minimum path width of the bridge should be at least 1.2m, and a railing should be added that is at least 1.0m high, which does not have gaps larger than 0.5m in diameter.

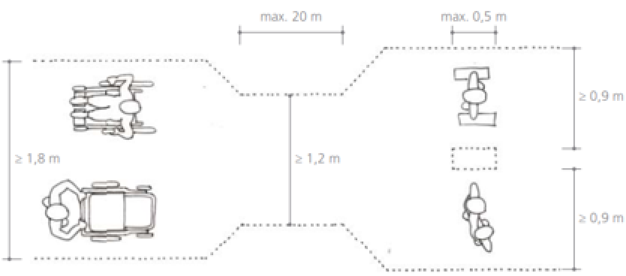


Figure 6.19: Illustration of the minimum width required for different types of pedestrians [125]

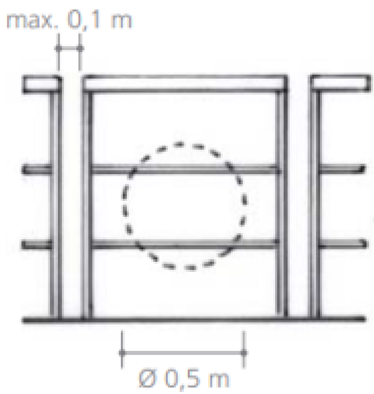


Figure 6.20: Illustration of the required dimensions for the railings of bridges [125]

6.4.7. Proportions and scale

With the length and width of the bridge known, and the size of the railing known, it is possible to adjust the shape and form to these. Taking the initial form as shown in Figure 6.17 , and setting the length to 17.5m and the width of each path to 1.2m we obtain the proportions and scale as shown in Figure 6.21. A This bridge would satisfy the requirements set by the context, to cross the distance to the pedestal,

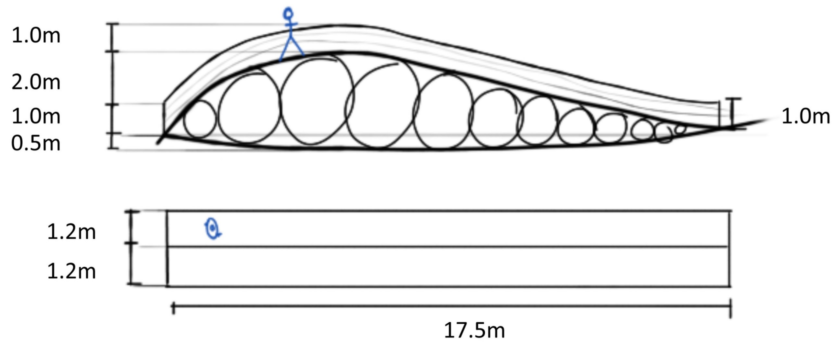


Figure 6.21: Proportions and scale of the initial bridge shape

but it would not be possible to design and manufacture a bridge of this scale within the scope of this project to be used a demonstrator at the Dutch Design Week. A physical prototype is very important to convey the message of the material, as this would allow the target group, and the visitors of the Dutch Design Week, to physically interact with the material and experience it firsthand, rather than seeing a render. A previous exposition of a bridge at the Dutch Design Week drew a great crowd of people, as shown in Figure 6.22, and would thus need to be very carefully designed. As there is a limited amount of time and material available for the project, it would not be possible to design a full-scale model on paper, and design and manufacture a scaled model for display at the Dutch Design Week.

As a result, the focus of the design process is shifted to the design of a demonstrator of the bridge, utilising the same design style as the full-scale model. For the scaled model, one path is removed to reduce the complexity of the bridge, and the length is scaled to fit with the length of the laminate off-cuts received (2 times the average length of the strips received). The proportions and scale of the scaled version of the bridge are shown inFigure 6.23.

Figure 6.22: Exposition of the MX3D bridge project as designed by Joris Laarman at the Dutch Design Week of 2018 [126]

6.4.8. Material and materialization

Now that the overall shape, form and dimensions of the bridge are known, the materials used in the bridge and the materialization can be further conceptualised. The bridge is split into two distinct elements, the deck and the railing. The deck is the wide beam element that carries the loads presented by the pedestrians, where the railing can provide walking support and is not a structural member. This division is made to keep the analysis of the structure as simple as possible.

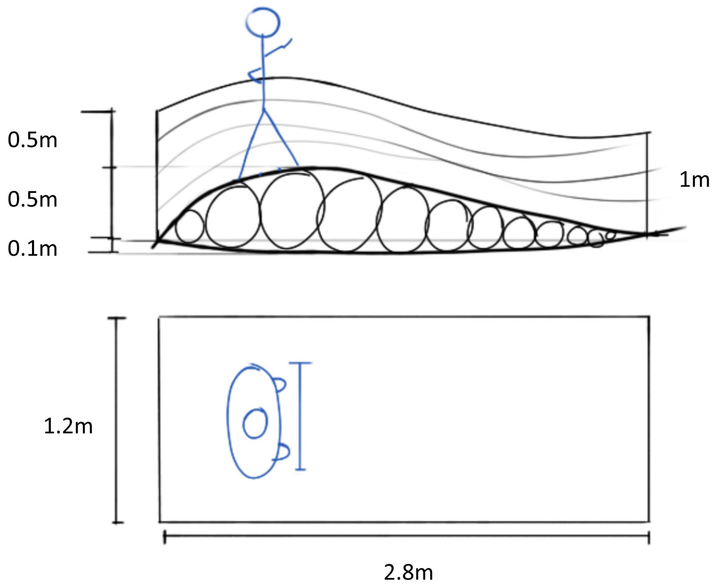


Figure 6.23: Proportions and scale of the demonstrator model of the bridge

The deck needs to be able support the loads presented by the pedestrians, and should provide a proper walking surface. Such a panel would be time consuming and complex to make from the laminate off-cuts, but another type of composite waste material could also be used. End-of-life wind turbine blades consist partially out of a glass fibre/foam sandwich, are curved and are generally stiff. From these EOL wind turbine blades (WTB), curved sandwich panels can be obtained which could form the basis for the deck. These panels are then reinforced by beams made from the laminate off-cuts to provide the strength and stiffness required. The use of additional composite waste material will increase the functionality of the bridge, and demonstrate the value of both the EOL WTB material as well as the laminate off-cuts for structural applications. The sandwich panels of the EOL WTB will also be a large part of the visual aesthetic of the bridge, when the pedestrians will be nearing the bridge, or walking on it. The aesthetics of the laminate off-cuts can be used here to make the bridge appear more exclusive and futuristic due to their reflections the laminate off-cuts have in the sun. Furthermore, bluish/white colour of the laminate off-cuts can be utilised to create an interesting contrast compared to the white coating of the sandwich panels.

As a result, the materialization of the deck using the EOL WTB sandwich panels and the beams from the laminate off-cuts is presented in Figure 6.24.

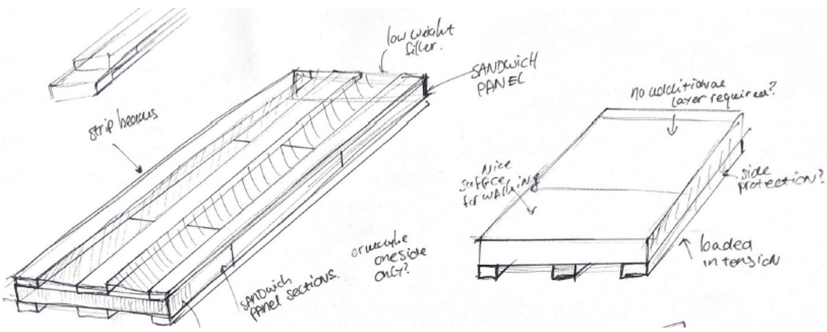


Figure 6.24: Materialization of the deck structure of the bridge, consisting of EOL WTB sandwich panels and beams made from laminate off-cuts

For the railing, the main functionality is to provide support for the pedestrians crossing the bridge, but it is also an important visual element of the bridge. Therefore, it presents the opportunity to demonstrate the aesthetic properties as well as the shaping possibilities of the material, in addition the functional value for structural applications shown by the deck. For the outline of the railing, an a-symmetric, sleek and streamlined form is used, with minimal decorative elements, to create a sense of speed, movement and efficiency. To fulfil its function as a support for the pedestrians, this outline has to be stiffened. This stiffening is partially done using vertical balusters but also horizontal elements. It is here that the shaping possibilities and aesthetics of the material are presented, through the stiffening elements. These elements follow influences of classic design styles for railings, but are also support the streamlined and efficient design of the railing. These elements show that even though the material has some defects, such as the resin squeeze out, delaminations or in-plane warpage, it can still be re-shaped into various forms and used to create functional and aesthetic elements. This is done by demonstrating single bend forming to stiffen the corners of the railing, coil forming to draw attention to the centre vertical baluster, twisting of the strips for attachment and stiffening of the end sections, and in-plane bending to allude to the aircraft rib structure, stiffen, provide support for the outline and show imply a sense of movement.

As a result, a conceptual outline for the railing of the bridge is presented in Figure 6.25, illustrating its form, stiffening elements and the shaping methods used to create these.

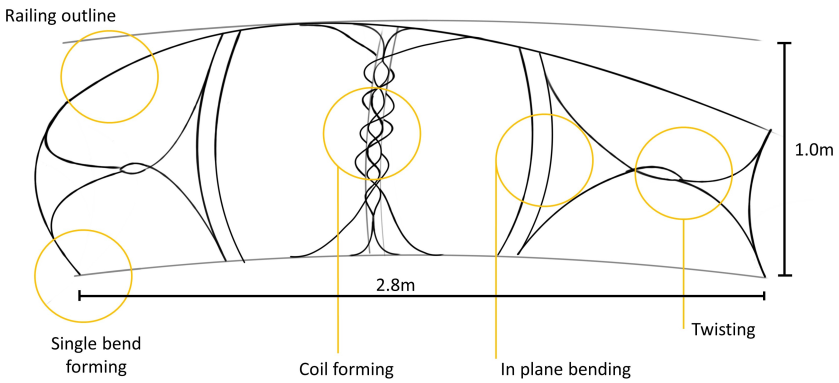


Figure 6.25: Illustration of the railing of the bridge, indicating its outline, stiffening elements and the reshaping methods to create them

6.4.9. Final conceptual design

A final conceptual design of the demonstrated is created as a result of the previous sections. This design details the dimensions, proportions and scale, determined from the dimensions obtained from the bridge context and the pedestrian bridge design guide. The design is presented in Figure 6.26.

This design features the use of laminate off-cuts in the railing, structural beam elements and the floor of the deck of the bridge. For the railing the aim is to demonstrate the shaping possibilities, and give the bridge a streamlined, modern and efficient aesthetic. The use of the material in the structural elements demonstrates the functional capabilities of the material whilst using a simple shaping method. By using the laminate off-cuts in the path on the deck of the bridge, the aesthetics of the material are highlighted and aim to give the bridge an exclusive and futuristic look.

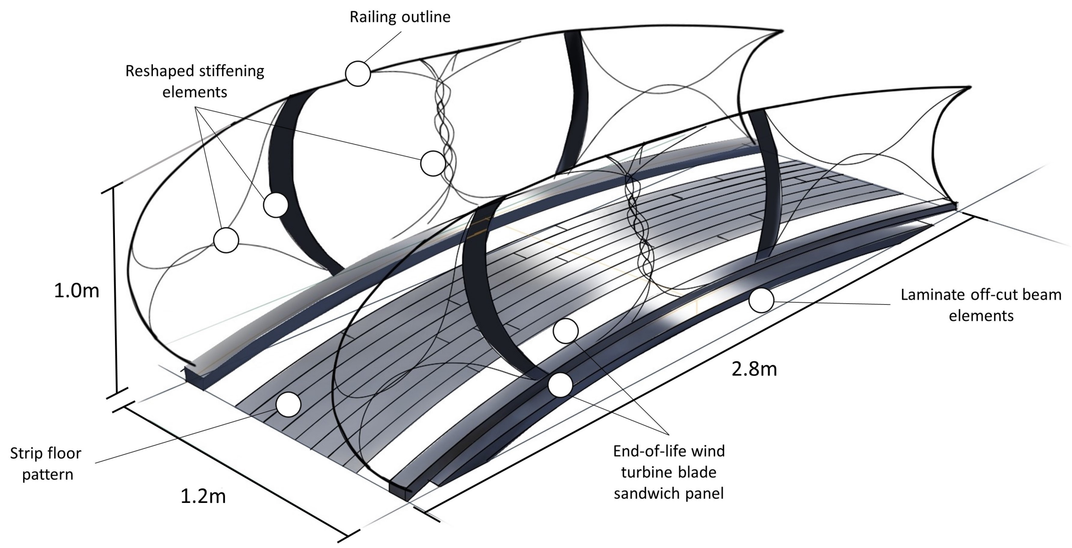


Figure 6.26: Final conceptual design of the demonstrator, detailing its dimensions, shape and form, materials and materialization

6.5. Demonstrator embodiment

This section provides a description of how the conceptual design is embodied into a detailed design. During the embodiment, the components of the demonstrator are further detailed, by using the dimensions and mechanical properties of the laminate off-cuts and the EOL WTB material. Furthermore, the manufacturing of the components is detailed through prototyping, resulting in a manufacturing plan for each component. With the detailed dimensions and manufacturing methods known, a detailed CAD model is constructed, and a manufacturing plan for each component is made. A final detailed design is presented at the end of this section.

6.5.1. Deck structure

The deck structure is the component that sits between the load carrying members of the bridge, and provides a support for the pedestrians to walk on. The deck structure is to be made from composite sandwich panels from EOL WTB blades, as these would provide good support for the pedestrians, and align with the use of EOL/waste composite material. To determine the geometry of the panels, a reference design of a wind turbine blade is used, which is made by Joncas [127]. This reference design is used as this provides the exact dimensions of the core materials and face sheets, and their mechanical properties.

The cross section of modern wind turbine blades consists of a load carrying box member, and a skin that follows the contour of the airfoil, where some parts are stiffened using a core material, as shown in Figure 6.27. Here, the load carrying box member, consisting of the shear webs and spar caps, are made out of the composite material only, whereas the skin sections also contain a core material for additional stiffness and weight reduction. As such, to retrieve sandwich panels from a wind turbine blade, the focus has to be on the top and bottom of the trailing edge of the cross section, or the top and bottom of the leading edge.

Three options are considered for the retrieval of the sandwich panels, as shown in Figure 6.28. The first option is to take it from the root of the wind turbine blade, which is an almost circular cross-section. However, this would make the curvature of the bridge too strong, which could make it look un-natural and uninviting to the users to try. The second option is to take a section along the length of the blade, which follows the curvature of the top of an airfoil. This option would result in an almost straight bridge with a slight curvature to the sides of the bridge. This would make the bridge appear more like straight panel, and have a limited appearance of actually being a bridge. The third option is to take two panels along the trailing edge of the blade, with the width of the panels in the lengthwise direction of the blade. When placing these panels opposite of each other, they create a panel that is slightly curved

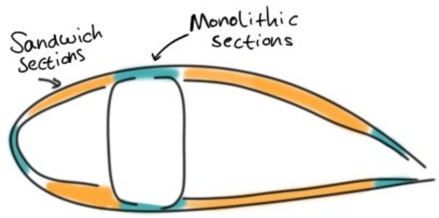


Figure 6.27: Simplified overview of a cross section of a modern wind turbine blade, demonstrating the locations of sandwich and monolithic sections within the blade

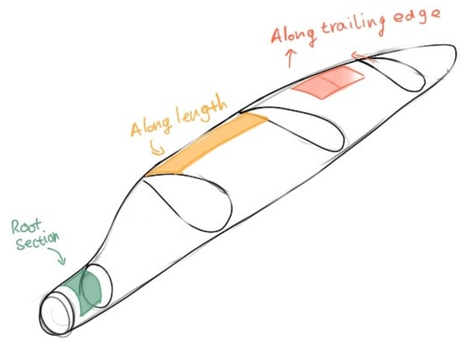


Figure 6.28: Three considered locations for the retrieval of the deck of the bridge demonstrator

along its length, with the top of the curvature in the middle of the panel as shown in Figure 6.29. This would give the appearance that the panel is a bridge that passes over something, whilst keeping the curvature slight enough for the users to try. This third option is chosen for the further embodiment of the demonstrator.

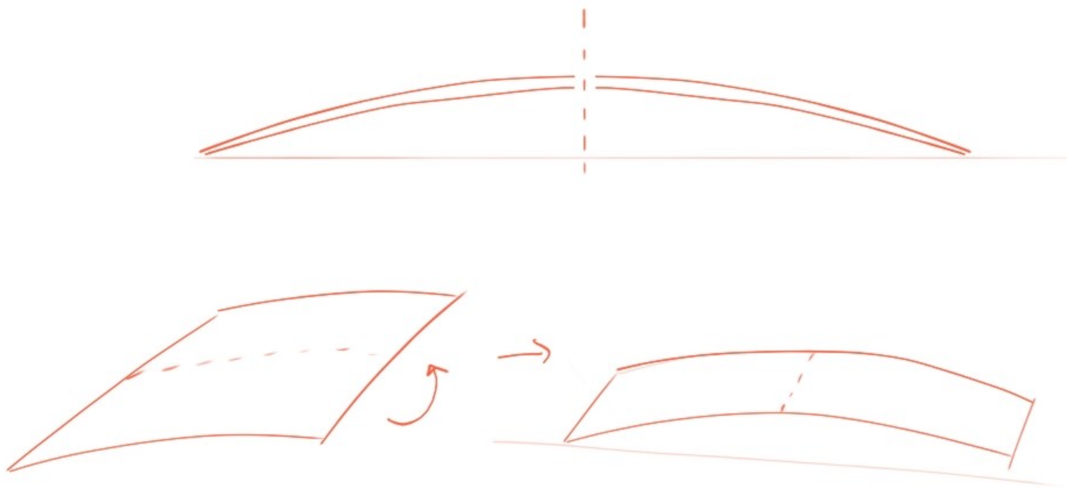


Figure 6.29: Cutting and rotation of the trailing edge element to create a slightly curved deck for the bridge demonstrator

The dimensions and mechanical properties of the skin and core material of the sandwich panel are summarised in Table 6.2. The dimensions of the skin and core material are taken at a distance of 43 meters from the root of the wind turbine blade as the length of each panel is roughly 1400mm at this location.
To summarise,

6.5.2. Off-cut beam elements

The beam elements spanning along the length of the bridge are designed to be the main load carrying elements of the bridge demonstrator. These off-cut beam elements are sized in such a way that the bridge complies to a maximum specified deflection and a safety factor on the stress inside the beam elements.

The reference load presented on the bridge demonstrator is taken from the pedestrian bridge design guide, which states that the bridge must sustain a load of $6kN/m^2$ [125]. Secondly, for the purpose of this initial analysis, a stress safety factor of 10 is required for the off-cut beam elements, to comply with initial first order analysis used for steel bridge design [112].

Table 6.2: Dimensions and material properties of the skin and core material of the sandwich panel. Dimensions and mechanical properties for the skin are taken from Joncas, and properties for the core are for medium density foam ($100kg/m^3$) [127][128]

Material property	Magnitude	Unit
Skin thickness	2.6	[mm]
Core thickness	26	[mm]
Glass fibre/ Epoxy elastic modulus	30	[Gpa]
Core material Elastic modulus	125	[Mpa]
Compressive strength GF/E material (S_{GF-c})	193	[Mpa]
Compressive strength core material (S_{C-c})	2	[Mpa]
Tensile strength GF/E material (S_{GF-t})	476	[Mpa]
Tensile strength core material (S_{C-t})	2.7	[Mpa]
Shear strength core material (S_{C-s})	1.7	[Mpa]

A model is constructed that first calculates the cross sectional properties of the beam elements, combined with the geometry and properties of the sandwich panel. This cross section is shown in Figure 6.30. The loading as defined previously is translated into a 2-D line load using the geometry of the bridge. Sandwich beam equations are then used to calculate the stress inside the off-cut beam elements and the core material, and the deflection of the beams at the mid-span is determined. A description of the calculation that is used can be found in Appendix N. The resulting geometry of the off-cut beam elements, safety factors and deflection of the bridge at mid-span is summarised in Table 6.3.

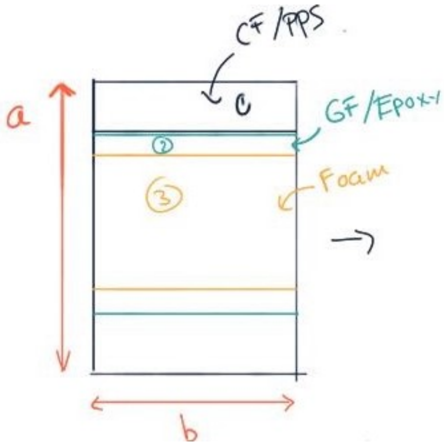


Figure 6.30: Cross section of the modelled beam, consisting of the foam core material, GF/Epoxy skins and the CF/PPS laminate off-cuts (not to scale)

The manufacturing of the beams made from the laminate off-cuts is explored by creating a prototype beam of similar dimensions, and using double sided tape to attach the laminate off-cuts. In this initial exploration the curvature of the beam is not taken into account, and the beam is stacked in a staggered pattern, as shown in Figure 6.31 to ensure that the gaps are in different positions. The thickest laminate off-cuts are used in this prototype, as allow for a high thickness of the beam to be reached whilst requiring the least bonding steps between the layers. A close-up of the prototype beam made from stacking the laminate off-cuts is shown in Figure 6.32.

From this exploration it is learned that the alignment of the laminate off-cuts in lengthwise direction can be difficult, due to the residual material on the sides of the strips, and the curvature of some strips along their length. Therefore, it is recommended that the sides with residual matrix are trimmed before incorporating these in the beam elements. Furthermore, it was observed that the gaps between the laminate off-cuts are not aligned easily, due to the large variance in the width and length of the strips. Therefore, the stacking pattern does not need to be strictly followed, but a stacking pattern based on

Table 6.3: Dimensions of the beams made from the laminate off-cuts, safety factors of the stresses in the beams, skin and core material and the resulting deflection of the bridge at mid-span

Property	Magnitude	Unit
Beam width	150	[mm]
Beam height	30	[mm]
Off-cut beam compressive stress safety factor (S_{tp-c}/σ_{TP_c})	11	[-]
GF/E skin compressive stress safety factor (S_{GF-c}/σ_{GF_c})	109	[-]
Core material compressive stress safety factor(S_{C-c}/σ_{C_c})	154	[-]
Core material shear stress safety factor (S_{C-s}/σ_{C_s})	2.36	[-]
Deflection at mid span	12.5	[mm]

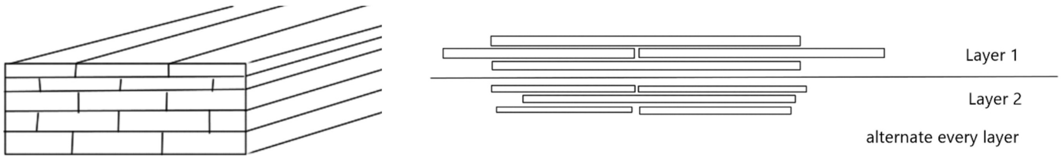


Figure 6.31: Stacking pattern for the beam made from laminate off-cuts

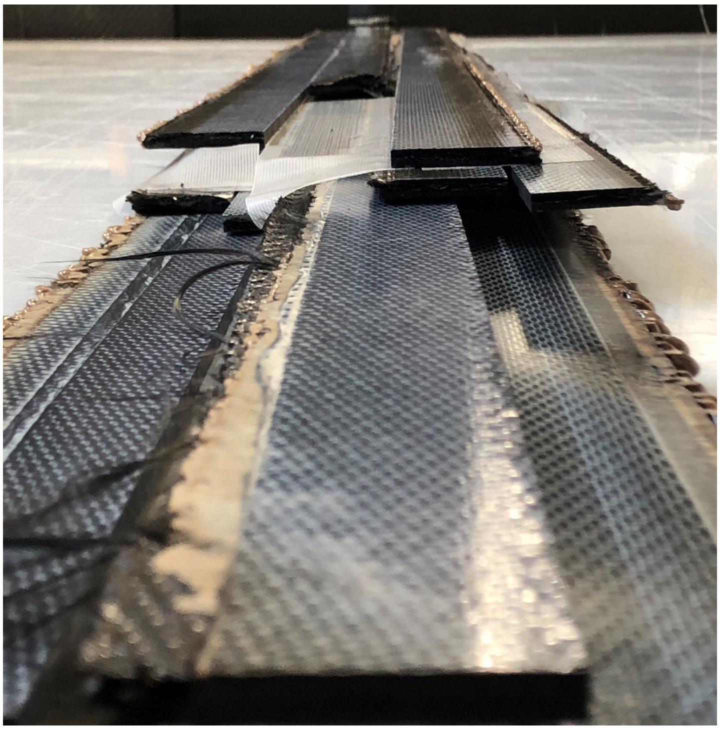


Figure 6.32: Close-up of the stacked laminate offcuts into a beam, with the double sided tape used to tie the off-cuts together

the total width of the beam can be used.

In a second round of exploring the manufacturing of the laminate off-cut beam elements, the curvature of the beam was incorporated and the trimming of the edge of the off-cuts was explored. A simple wooden mould with a aluminium plate was made according to the curvature of the sandwich panels, which can be used to create the curvature of the off-cut beam during bonding. When placing the laminate off-cuts on this mould, it is clear that support is needed on the top of the laminate off-cuts to ensure that these comply to the curvature of the mould, as shown in Figure 6.33. The trimming of the edge with residual thermoplastic matrix material is also explored by using a water-cooled diamond coated saw that is suitable for thermoplastic composite materials at the faculty of Aerospace Engineering. The

Figure 6.33: Close-up of the laminate off-cuts when placed on the curved wooden mould

resulting cut is shown in Figure 6.34. From this exploration it is apparent that the edge with residual thermoplastic matrix material curves outwards, and that the saw used is not suitable for making longer cuts, partially due to the length of the saw and also due to the manual operation of the saw. To trim a larger amount of laminate off-cuts, a more rigid saw is required.

Figure 6.34: Laminate off-cut with the partially trimmed off residual matrix edge, demonstrating the curvature after trimming

To summarise, the off-cut beams are sized according to the bending load presented on the bridge, and a manufacturing tool has been designed that can be used to give the beam its curvature during stacking and attachment. However, additional work has to be put in trimming the edges of the laminate off-cuts, before these can be stacked in to a beam element.

6.5.3. Deck off-cut path

The laminate off-cuts are also used on the top of the deck panels, to increase the visibility of the material, and demonstrate the aesthetic properties of the material. The creation of such a panel for the deck is explored by making an outline of the bridge in a 1:1 scale, and placing the laminate off-cuts in a section of 90 centimetres wide. For the creation of this off-cut path, only the thinnest laminate off-cuts are used, as these lend themselves less to be used in beam applications, as it would require many bonding steps to reach a higher thickness. The outline of the bridge with a representation of the off-cut beam elements is shown in Figure 6.35. The thin strips also present with a large in plane curvature

Figure 6.35: Outline of the bridge with the off-cut beam elements on either side

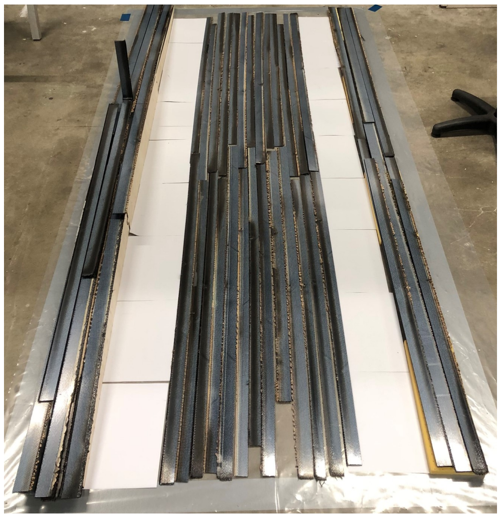


Figure 6.36: Slightly curved path made from the laminate off-cuts, with the white paper creating the contrast between the EOL WTB deck material

along their length, which makes alignment into a straight pattern, as presented in Figure 6.26, more difficult. To do so, the laminate off-cuts would have to be trimmed, which also removes the appearance of it being a waste material. However, the in-plane curvature is constant in its direction, the side with the residual matrix material always has the smaller radius, which allows for the creation of a different pattern. To create the path, each of the strips are aligned with their curvature, making a wide curved path out of multiple smaller curved elements. For the second part of the path the curvature is reversed, creating an S shaped path along the length of the bridge, to steer the path in the lengthwise direction of the bridge. The path made from the laminate off-cuts is presented in Figure 6.36.

In this way the curvature of the laminate off-cuts is used as a feature, allowing for the creation of a curved path, and the appearance of it being a waste material is maintained. The path now also demonstrates the possibilities of using the defects of the material to the advantage of the designer, whilst highlighting the appearance of the material in the process.
To summarise, the thinnest laminate off-cuts can be used to create a path over the deck of the bridge, and a sightly curved path instead of a straight path can be made across the bridge by using their in-plane curvature, demonstrating that possibilities of using the defects in the material to the advantage of the designer.

6.5.4. Railing

For the embodiment of the railing of the bridge, three parts can be distinguished: the railing outline, the formed stiffening elements and the handrail. The railing outline and stiffening elements are the main aesthetic elements of the railing, and showcase the shaping freedom and functionality of using a waste material. It is not intended that the users interact physically with these elements, as they can feature sharp edges from the forming process. For the interaction with the railing a handrail is added to the outline of the railing, which is designed for the users to interact with. Each of these elements are further detailed through the creation of prototypes, providing insights into the manufacturing process and the dimensions.

For outline of the railing, the manufacturing and dimensions are explored by elastically bending these in place on a welding table, and using double sided tape to adhere the off-cuts. This process is shown in Figure 6.37. During this exploration a thickness of 5mm for the top layer of the railing was used, and a thickness of 3mm for the stiffening inner elements was used. This exploration showed that even though the strips were adhered using the double sided tape, the elastic bending required a large amount of force that resulted in a a large residual force inside the material. As such, as soon as the clamps of the welding table were removed the form fell apart. As such, the residual stress inside the material will have to be released to create the form of the railing. The welding table did provide a good working surface, and was such also used in a second exploration session. During this second session a thermoplastic strip was used, to mimic the behaviour of the laminate off-cuts, and these strips were locally heated using a hot air gun to release the tension and keep the bent shape. This process is shown in Figure 6.38. This exploration revealed that this worked well for the more local bends, but a mould surface is required to make a bend comply over a larger distance. The manufacturing of the local single

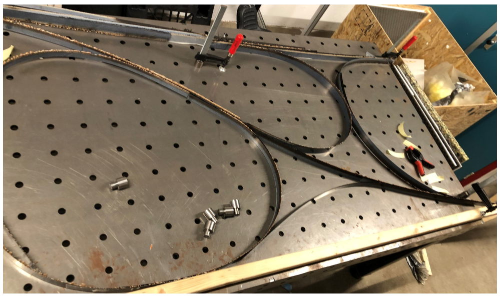


Figure 6.37: Elastically bent railing shape on top of a welding table, releasing from the clamp as soon as the supports are removed

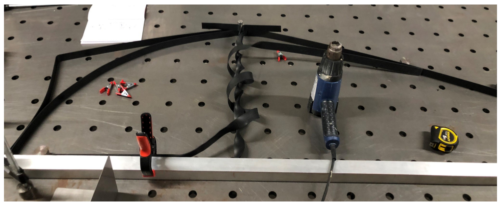


Figure 6.38: Thermoplastic strip material locally heated and bent into shape, keeping its form after the supports are removed

bends in the railing is also explored by using a hot air gun to locally heat the material, and using a round stock to as a forming tool. The process and result are shown in Figure 6.39 and Figure 6.40. The local heating using a hot-air gun proved succesfully as the material only melted locally. However, significant folds were created during the forming process due to a lack of pressure in the bend area. These folds can be considered a defect that is introduced into the material, but these do add additional area to the bend, which can increase the stiffness of the bend but reduce its strength. As such, the defects caused by the single formed bending could provide additional functionality. The manufacturing of the

Figure 6.39: Setup of the single bend forming using a hot-air gun, to locally heat the material

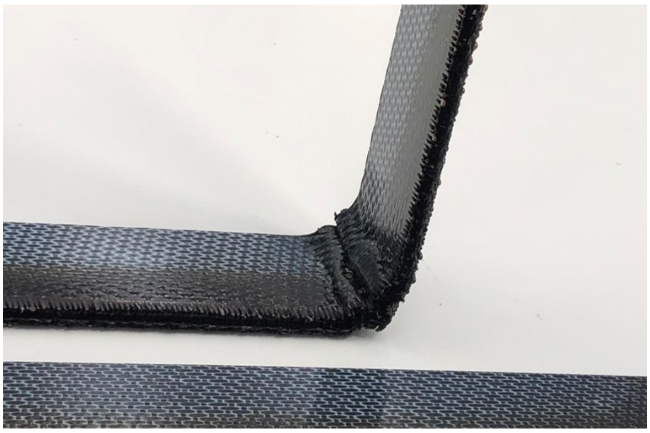


Figure 6.40: Folds present in the single bend made using local heating with hot-air gun

curled element is also explored, using a large round stock, and a hot air gun to locally heat the material and form it around the stock. The process and result of this exploration are shown in Figure 6.41 and Figure 6.42. The local heating using the hot-air gun allowed the material to locally deform and comply with the round stock, although there are some slight folds present in the material. Furthermore, as the hot air gun can only heat the material locally, it could not fully comply with the round stock.
The manufacturing of a twisted elements from the laminate off-cuts has only been explored by using a thermoplastic strip, rather than a thermoplastic composite strip. The process involved stacking two strips and rigidly clamping these on one end. A hot air gun is used to locally heat the material, whilst

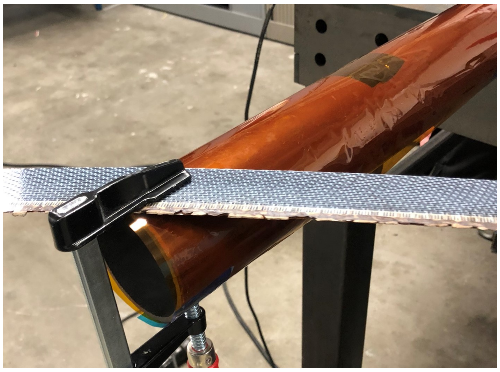


Figure 6.41: Setup of forming a curled section from a laminate off-cut, using a using a hot-air gun and a round steel stock

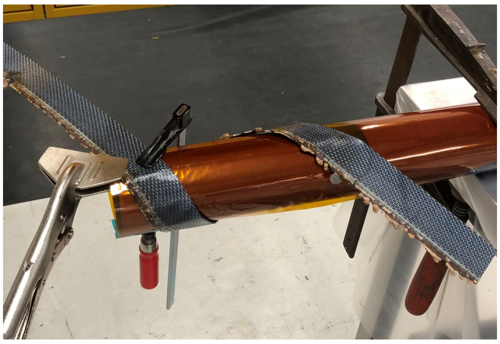


Figure 6.42: A laminate off-cut curled as a result of the prototyping process

the other end of the stacked strips is twisted. As the strips heat up these become compliant and upon cooling set in their twisted position. The result is shown in Figure 6.43. As the twisting continues over the length, the shape twists more, due to the reduced effect from the clamping.

Figure 6.43: Thermoplastic strip shaped into a twisting pattern, using a hot air gun to locally soften the material to allow for twisting

To summarise, creating the shaped features, including the single formed bends, curls and twists, of the railing is possible through the use of a hot air gun, and simple tooling, but does result in defects within the material. For shaping longer sections of laminate off-cuts a mould is required to ensure the material follows the right shape.

6.5.5. Handrail

The design of the handrail should be such that it is clear for the user that this element is for touching, and that they should be comfortable with grabbing this. To make the intent of the handrail clear, the handrail is designed to extend towards the user, to nudge the user into interaction. The handrail is also designed to be stiff, to demonstrate the mechanical properties of the material when it is grabbed by the user. As such, a thick laminate off-cut is used for the core part of the railing. To improve the fit of the hand of the user to the handrail, a slightly curved section is added on top of the railing. This provides a more gentle fit with the palm of the hand, and in turn also adds additional bending stiffness to the handrail. A small curved section is used for the initial design of the railing, rather than a full circular cross section, to limit the amount of material used and contain the manufacturing complexity.

A prototype of the handrail was manufactured using a hot-air gun, a round hollow steel stock, and a small curved plate of aluminium. The core part was manufactured by locally heating the laminate off-cut, using a hot air gun, and then folding it on top of itself. The result of this process is shown in Figure 6.44. An additional step in the handrail is made by locally heating the laminate off-cut, and draping it over the round steel stock to make a bend with a large radius. A similar process is followed for the second step, and the result of this process is shown in **??**. The curved section for the top of the handrail is made by locally heating the material, and then pressing it to comply with the round steel stock, using a small curved aluminium plate. The result of this process is shown in Figure 6.46. The final prototype of the handrail with the curved section attached using double sided tape is shown in Figure 6.47.

Figure 6.44: First fold made for the core part of the handrail

Figure 6.45: Single formed bends with a large radius made as a continuation of the fold

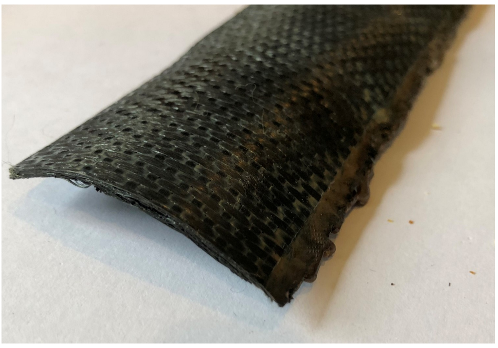


Figure 6.46: Top section of the handrail that is formed along the radius of the round stock

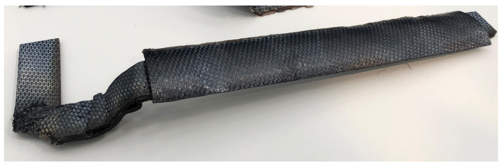


Figure 6.47: Assembled top curved and core part of the handrail, using double sided tape

The prototyping process showed that it was difficult to heat a larger section of a thick laminate off-cut to form a fold, and that this required extensive heating and folding force to form. As a result, excessive defects formed during the process. Similar issues were observed during the forming of the large radius single bends in the thick laminate off-cut. For the curved section, the heating and forming process worked as expected, but slight deformations and misalignment of the shape are observed after forming, due to the flexibility of the forming tool used. The appearance and surface quality of the curved section was also affected during forming, as the appearance changed from glossy to matt, and the surface changed from smooth to textured, where the weave creates the texture. The changes in the surface appearance can be seen by comparing the surface quality of Figure 6.44, with **??**. This can be the result of the low pressure on the surface during forming, and improper processing parameters.
To summarise, a handrail is designed to be the interactive element of the railing. The form of the handrail extends towards the user to nudge them into interaction, and its structure consists of a thick core section that provides the stiffness, and a curved thin section on top that provides a surface to grip.

The prototyping process showed that it is necessary to use extensive heating and force to fold a thick laminate off-cut, and that the surface appearance and texture is affected by the forming process.

6.5.6. Abutments

The aim of the abutments is to support the load bearing components of the bridge demonstrator, and counteract the horizontal force caused by the arch of the bridge. These components are designed to be hidden as much from the public, not to cloud the aesthetics of the bridge. As such, the abutments are painted black, and are designed to retract underneath the bridge to have as little an effect on the aesthetics of the bridge as possible. The abutment as placed on one side of the bridge is shown in Figure 6.48. As these will be placed on the ground at the exposition location, and need to be heavy to

Figure 6.48: Abutment at the end of the bridge, designed to retract underneath the bridge to hide its aesthetics

resist the horizontal load, they will be cast from concrete. The concrete will be cast into a wooden mould, with the outer dimensions of the abutments, ensuring that the concrete has the correct shape. Once the concrete dries, it can be removed from the mould, and placed underneath the bridge demonstrator.

6.5.7. Final embodied design

As a result of the detailing of the compnents of a bridge demonstrator, a CAD model of the final embodied design of the bridge is made. This CAD model is used to make a render of the final embodied design, which is presented in Figure 6.49 and Figure 6.50. Close ups of the railing, deck off-cut path and the handrail are presented in Figure 6.51, Figure 6.52 and Figure 6.53.

Figure 6.49: Side view of the final embodiment of the bridge demonstrator design

Figure 6.50: Back view of the final embodiment of the bridge demonstrator design

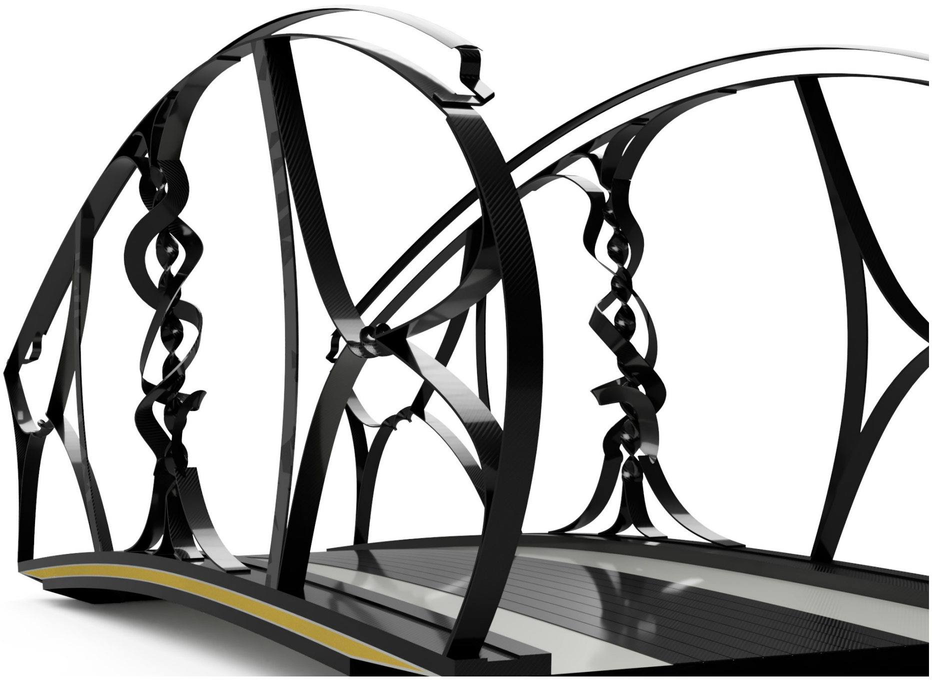


Figure 6.51: Close side view of the front of the railing, showing the outline, front twist and centre curl

6.5.8. Manufacturing plan

By using the experience obtained from making the prototype versions of the components of the bridge, and the detailed cad model, a manufacturing plan for each component is made. Each component is indicated with a number as shown in Figure 6.54. The manufacturing plan detailing the manufacturing approach and the required materials is presented in Figure 6.55.

Figure 6.52: Top view of the bridge demonstrating the S shaped path created from the laminate off-cuts across the deck of the bridge

Figure 6.53: Close view of the attachment and shape of the core part of the handrail, and the curved top section extending along the length of the railing

Component No.	Qty.	Description
1	2	Upper off-cut beam
2	2	Lower off-cut beam
3	2	Bridge abutments
4	2	Railing outline
5	2	Front railing twist
6	2	Centre railing twist
7	2	End railing twist
8	2	Centre railing curl
9	2	Flat curved railing elements
10	2	Handrail
11	2	Deck off-cut path

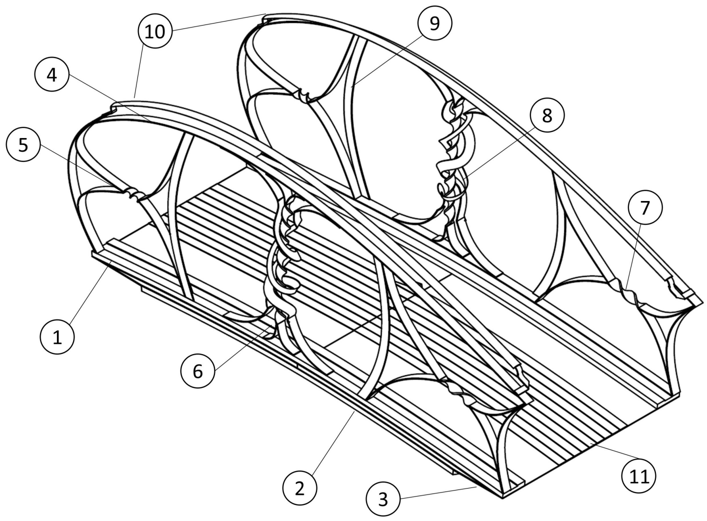


Figure 6.54: Overview of the different components of the bridge demonstrator, with their quantity and their location inside the demonstrator

Component No.	Qty.	Descr.	Manufacturing	Required materials
1	2	Upper off-cut beam	Trimming of side with residual matrix, placement on laser cut wooden moulds, and attachment into a beam using an adhesive	Wooden laser cut mould, weights during gluing and an adhesive.
2	2	Lower off-cut beam	Similar as above	Similar as above
3	2	EOL WTB deck	Milling of foam core to dimensions, shaping using hot air gun Wet-layup of skins to shaped foam core, one at a time.	Glass fibre weave, epoxy, foam block and hot air gun
4	2	Bridge abutments	Casting of concrete into a wooden mould, and spray painting to black/grey colour after curing	Fast setting wet concrete pour mix, water and spray paint
5	2	Railing outline	Shaping using laser cut wooden moulds, heating using a hot air gun and attachment through an adhesive	Adhesive, wood for laser cutting and a hot air gun
6	2	Front railing twist	Clamping two strips on one end, applying twist on one end and using a hot air gun to twist the strips into shape	Hot air gun
7	2	Centre railing twist	Similar as above	Similar as above
8	2	End railing twist	Similar as above	Similar as above
9	2	Centre railing curl	Clamping the strip on one end of a round stock, and curling the strip around the round stock whilst locally heating the material	Hot air gun, round material stock
10	2	Flat curved railing elements	Single bend forming at the top of the strip, attachment to the outline using an adhesive	Hot air gun, single bend tool and an adhesive
11	2	Handrail	Folding and single bend forming using wooden tools, whilst locally heating the material using an hot air gun. Attachment between the core, curved top and railing outline done using an adhesive	Adhesive, single bend forming tools
12	2	Deck off-cut path	Alignment of the strips into a pattern on the deck, attachment to the deck using an adhesive	Adhesive

Figure 6.55: Overview of the manufacturing methods and materials required for the manufacturing of each component of the bridge demonstrator

7 Final designs & process evaluation

7.1. Introduction

This chapter of the report reflects on the design of the corrugated sandwich beam and the bridge demonstrator, and the design process that is used to design these. The evaluation of both designs is done according to the initial design criteria, and evaluating how well both designs match their intended goal. The design process of the structural member and the bridge demonstrator is evaluated by reflecting on the entire design process, and focusing on the methods used to explore the material properties and new potential applications. From the insights of this reflection, a framework for designing new applications from waste composite materials is created.

7.2. Corrugated core sandwich beam

The aim of the design of the structural member was to discover the technical functionality that the laminate off-cuts can offer for engineering design. The starting point of this exploration was the laminate off-cut material, and four criteria that should guide the design process. These criteria should ensure that the design of the structural member suits the variability of the material, is possible to manufacture in the given timeframe, can result in a high-performance structure and be adaptable to other functionalities. As a result of this design process, the corrugated core sandwich beam is developed, which will be evaluated on these four criteria in the next sections.

7.2.1. Adaptable to material

The form of the corrugated sandwich beam was deemed to be good at adapting to the variation in geometry and mechanical properties of the material, as this could be compensated in multiple areas of the beam. Through the creation of the analytical model and looking back at the manufacturing possibilities this criteria can be evaluated in further detail for the final design.
From the analytical model, as described in Section 5.3.3 it can be derived that the main geometric and material properties governing the mechanical performance of the structure are the cross sectional area of the face sheets, its area moment of inertia and the elastic modulus of the material. As laminate off-cuts can be stacked, as described in Section 3.2.4, any variability in these properties can be compensated by the addition of new material to either the strip in question, or to another part of the sandwich beam.

Another method of adapting for the variability is the option of changing the geometry of the beam, which in turn affects its properties. To create a constant stiffness over the length of the beam, with a changing cross section of the bottom and top face sheets, the height of the corrugation can be tailored to suit the exact stiffness required. In this way, the top and bottom face sheets can be constructed separately out of multiple laminate off-cuts, and the geometry of the corrugation can be determined from their resulting cross-section.

A limitation of this evaluation is that this criteria is only evaluated by using a theoretical model, which is not validated with mechanical testing. Through a dedicated design case with functional requirements the model could be validated using mechanical testing, which could indicate whether the compensation of the properties actually performs as suggested.

7.2.2. Ease of manufacturing

The corrugated sandwich beam form also scored well on its ease of manufacturing a high-quality form, as it only requires single bend forming that can be done with common tooling, and its assembly is straightforward. To validate the ease of manufacturing single bends, a experimental test is performed to make single bends in material samples.

The manufacturing of single bends has been explored on a prototyping basis, using common available tooling at the faculty of Aerospace Engineering, and the processing parameters derived in Section 3.3.3. The results proved that single bend forming is possible using common tooling, and that following the processing parameters forming was possible. From the results of the test, a manufacturing process for making the corrugated core out of a strip of thermoplastic composite material is proposed, but has not been further tested.

The local assembly of the thermoplastic composite material has not been explored in detail, but initial results from the adhesive bonding of PVC demonstrated that this process was relatively straightforward. With the identification of a suitable adhesive for the material, the local assembly process, as shown in Figure 5.26, could be followed for creating the local bonds. However, this has not been tested for the laminate off-cuts.

A limitation of this evaluation is the lack of a dedicated shape that could act as a benchmark to which the manufactured shape could be compared to. The results showed that making a single bend was possible with common tooling, but the quality of the bends was not tested. Dedicated tooling and a testing method would be required to determine whether the manufactured bend is of high-quality, but due to the limited available time for the project this was not validated in further detail.

7.2.3. Structural performance

The corrugated sandwich beam also scored good on the ability to create a high-performance structure, as it would be able to tailor the geometry of the face sheets and corrugated core to a required performance. This criteria is evaluated on a theoretical basis, using the results from the form exploration and the analytical model.

The form exploration showed that the properties of the parts of the corrugated core sandwich can be tailored to a required performance load case, as shown in Figure 5.16. Depending on the function and requirements of the structure, the form or geometry of the parts can be tailored to deliver the specified equivalent properties. This is confirmed through the analytical model, where mathematical relations are derived between the beam geometry and its properties. The analytical model also provided mathematical expressions for the prediction of failure of the structure, which can be used to further increase the performance of the structure.
The focus within the design of the corrugated sandwich composite beam was on the mechanical performance of the beam, such as stiffness and strength, and not so much on the toughness, temperature and chemical resistance. The performance of the thermoplastic composite material properties of the laminate off-cuts can be compared to another aerospace material, like Aluminium 7075-T6, to evaluate its performance for weight critical design. This comparison is shown in Table 7.1, where it is apparent that more laminate off-cut material is necessary to match the strength properties of the aluminium, but less is needed to match the stiffness of the aluminium. Additionally, when taking into account the toughness, chemical and temperature resistance of the material, it is dependent on the application whether the material is actually of higher performance.
A limitation of this evaluation is that the results of the analytical model have not been validated through mechanical tests, and that the strength of the material has been estimated using results from literature, which might not accurately represent the strength of the material. By validating the analytical model and determining more accurate material properties, the performance of the structure would have been more realistic, and made it possible to compare to other structures. Furthermore, by not having a detailed application for the structural element, an evaluation of the performance of the structure is difficult to perform.

Table 7.1: Comparison of the specific strength and stiffness of the laminate off-cut material and aluminium 7075-T6 [129]

Material property	Aluminium 7075-T6	CF/PPS laminate off-cut	Unit
Density	2770	1550	$[\frac{kg}{m^3}]$
Young's modulus (E)	69	56	[GPa]
Compression strength (σ_{comp})	390	193	[MPa]
Comparison			
$\frac{\rho_{comp}}{E_{comp}} / \frac{\rho_{al}}{E_{al}}$	0.69		[-]
$\frac{\rho_{comp}}{\sigma_{comp}} / \frac{\rho_{al}}{\sigma_{al}}$	1.13		[-]

7.2.4. Adaptable functions

The corrugated sandwich beam also scored good on its ability to adapt to other functionalities in its next life, mainly as it is in the form of a standard construction element. This criteria is evaluated by looking at the analytical model, the manufacturing of the beam and the design opportunities.

To use the beam structure in a next life, the properties of the structure would need to be known. As the geometrical information of the structure is free to obtain, there a no constraints for a caliper to measure the widths and thicknesses of the elements, the analytical model can be used to estimate its properties. When the properties are not satisfactory for the next life cycle, the analytical model can be used to design a suitable geometry, which can be created by stacking more laminate off-cuts either on the top or bottom face sheet of the beam. In the case of multiple beams, these can be stacked together, as shown in Figure 5.21, to create new structures. In this way the corrugated sandwich beam can be seen as a modular structural element, that can be adapted to new functionalities.
A limitation of this evaluation is that it has only been described in theory, and not actually executed due to a lack of initial applications. Several applications have been proposed in Section 5.4.4, but a detailed design of the corrugated sandwich beam lacks. A more detailed design would help narrow down potential re-use cases and could provide the basis for the adaptation of the structures for new applications. Furthermore, this evaluation lacks taking into account the wear of the structure during use, and does not consider the manufacturing aspects related with re-processing the corrugated sandwich beam structure by adding more strips to the face sheets.

7.3. Bridge design

The aim of the bridge demonstrator was to simulate creative thinking by designers and engineers about the use of thermoplastic laminate off-cuts, as defined in Chapter 4. In order to do so, the design was intended to grab the attention of the users, be relevant to them and convey a strong message about the use of the material. To evaluate whether the design meets its intended goal, an evaluation session with the target group was performed.

7.3.1. Evaluation method

The evaluation of the final concept was performed at the faculty of Industrial Design Engineering, as this is where the target group could be reached. As no complete prototype of the design could be realised in time, the evaluation used the prototypes made during the railing and off-cut beam manufacturing exploration, to represent the parts of the railing. Furthermore, a picture of the final concept bridge design was printed and available during the session. The setup used for the evaluation is presented in Figure 7.1. First, the participants were asked to sign a consent form for their participation in the evaluation. Afterwards they were given a short introduction of the project and the material in front of them, which was followed by a series of questions. The first questions guide the participant to explore the traits and the shaping possibilities of the material, which is followed by a presentation of the final concept bridge design. The participants are then asked to explore and new applications for the material, taking into account their experience with the material, the shaping prototypes and the final bridge concept design. Afterwards, the participants are asked whether the final concept design helped them in coming up with new applications. To evaluate the usability of the handrail, the participants are

Figure 7.1: Setup used for the evaluation of the final bridge concept

also asked whether they would interact with the handrail in its current state, and explain their reasoning why. A full list of questions for the evaluation and the consent form used for the participants can be found in Appendix O

7.3.2. Results

Three participants, two IDE students and one civil engineering student, were found to participate in the evaluation. For the exploration of the properties of the material, each participant found different properties of interest with the main focus on the aesthetic and experiential properties. Two of the participants were clearly surprised by the low weight and stiffness of the material, and noticed the high-pitched ringing sound when tapping the material. The third participant focused on how the defects of the material affected the appearance and his initial perception of the material from being high-performance, to being a waste material.

During the exploration of the material and after seeing the final concept design, the participants came up with several ideas. Ideas such as a sound barrier or an acoustic guitar were proposed form the almost metal like ringing noise of the material. Another idea that included the reflective properties of the material and the shaping possibilities was a lamp shroud, allowing for complex forms that can be shaped to create a certain reflection or shadow. One idea that used the defects of the material was a chair made from burnt/charred wood in combination with the laminate off-cuts, where the 'burnt' edge of the laminate off-cuts can be used to complement the design of the chair. Another proposed idea is that the appearance and perception of the material, it being exclusive, expensive and high-performance, can be utilised to change the appearance of a product and increase its perceived value or performance. More functional designs were also proposed, suggesting that these can be used as structural members due to their low weight and high mechanical properties.

When asked if the the final concept design helped the participants to come up with new applications two of the three participants responded positively. The participants noted that his was mainly due to the shaped prototypes that present during the evaluation. The third participant focused mostly on how the defects from production change the material aesthetics, and did not see how this is utilised in the final concept design. As such, the final concept design does perform positively in stimulating creative thinking by both engineering and design students, as they were able to come up with several varying ideas on how the laminate off-cuts can be re-used in new applications.

7.3.3. Limitations

Limitations of this evaluation include the limited number of participants for the evaluation, the lack of a full scale physical demonstrator of the final design. As only a limited number of participants were available for the evaluation of the final design concept, the outcome of the evaluation can still change if a larger group is used. Furthermore, the lack of a full scale physical demonstrator could have made the connection between the prototype samples present and the final concept design less clear, and reduced its effectiveness.

7.4. Design process

The aim of this section is to gain insights from the followed design process, and create a design framework from this that can guide designers and engineers in designing new applications from waste composite material.

7.4.1. Design method

The double diamond design method was selected as the design method to be followed for this project. This design method consists of alternating diverging and converging phases in the design process, to reach a final outcome. Whilst this method was fixed from the start, the tools to be used during the project were not well defined, as much was still unknown about the material and the final outcome. As the project progressed, more information became available on the material to be used during the process, which resulted in rethinking steps already taken and making decisions with incomplete information. With more information becoming available throughout the project, new tools or processes also had to be sought out, hampering the progression of the project. The formulation of a design vision and design criteria steered the design process, and made making decisions that align with the project goal easier. During the later embodiment phases of the project, new information on the material was also obtained, which could have steered the decision making in earlier phases as well.

Knowing this, the selection of a design method at the beginning of the project had to be more careful, and consider the iterative nature of the project. The structure of the design process of the project did not allow for enough iterative steps, which made the progress slower it had to be, and made the integration of new things learned about the material properties or processing difficult. With a more iterative approach, the new things learned about the material could have been integrated easier and sooner, which would give more time for the embodiment of the design.

7.4.2. Material exploration

Throughout the project, several experiments or tests were undertaken to explore the properties of the material, and the processing possibilities. These experiments include the single ply off-cut press experiment, the single bend forming experiments, the detailed visual defect inspection, the outside reflection experiment and the manufacturing of the prototypes for the bridge demonstrator railing. These experiments revealed the properties of the material and demonstrated what suitable processing methods were. Each of these experiments was undertaken at different phases in the project, sometimes as the material was not available, but sometimes because there was no need yet to perform the experiment. This meant that in some cases, information about the material was only discovered later in the project, when this would have been valuable at an earlier stage as well. As the project progressed, it also became clear which aspects of the material are affected by it being a waste material. Had these aspects been more clear from the beginning, more structured and targeted experiments could have been performed to learn more about how the material is affected.

Knowing this, the exploration of the material properties should have been more structured, and executed at the beginning of the project. In this way it would have saved time, would have allowed for a deeper exploration of the material properties, and made integration of the results into the design process easier. By knowing which aspects of the composite material are affected by it being a waste material, it is also possible to steer the design process in a certain direction, and put the focus on exploring that aspect of the material (or not).

7.4.3. Application design

The process of finding new applications from the laminate off-cuts used the design vision and criteria as a leading element. This design vision left the message to be conveyed by the material open, and the properties and processing possibilities of the material were used to give shape to this message. In the process, several tools were used to stimulate the ideation process including mind-mapping, group brainstorming and design drawing to discover. These tools proved effective for generating ideas, but the as the design vision and criteria were loosely defined, several rounds were required to align these with the goal of the project. Through an iterative process of evaluating and defining the design vision, design criteria and the generated ideas, a final idea was selected. Knowing more about the value of the material, through exploring its properties, would have been useful in this phase as this could be used to narrow down message to be conveyed, or aspect to be shown.

Knowing this, the process of defining the design vision and design criteria should have been more integrated with the exploration of the properties of the material and its shaping possibilities, as this would allow for a more targeted use of the ideation methods.

7.4.4. Re-capturing value through design

Taking the insights obtained from reflecting on the design process of this project, and discussing this with fellow students that completed a similar type of project, a new design framework for designing new applications from composite waste material is proposed. The aim of this framework is to provide structure to the process of designing new applications from composite waste materials. This framework consists of three distinct phases: source and selection, exploring value and capturing value.

The first phase of the framework focuses on identifying different composite waste flows, and selecting a suitable material for the rest of the process. This phase can be centred around a product, or parts of a product that are made out of composite materials. Tools such as product journey mapping can be used to highlight the composite waste flows coming from the product over its lifetime and during the production. As there is a wide variety in the types matrices and fibres that a composite material can have, it is important to make a decision for a specific type (or multiple types) early in the process, and keep the analysis of the different types to a high level. This is to ensure that there are enough resources left to study the chosen material in detail later in the project. The selection criteria are dependent on the overall goal of the project, and were in the case of this project based on the availability of the material, the recurrence of the material within the process, the purity of the waste stream and the form that the material is in. According to these criteria, the different waste types can be analysed on a high-level and a decision can be made.

The second phase of the framework focuses exploring the material to increase the understanding of the material by the user of the framework, and uncover the value of the material. This phase is characterised by two main parts, the processing possibilities and the material characteristics. The framework provides a structure that details the aspects of the material character and the processing of the material, to provide guidance for the user of the framework. However, many of the aspects of the material are affected by each other, where these relations differ for varying composite material types, and it is in this phase that these relations can be discovered. It is through exploring the processing, context and properties of the material, that the value of the material can be discovered.

The third phase is centred on capturing the uncovered value of the material into new applications. This is an iterative phase around three parts: value selection, design vision and the application. The design vision is the leading element among these three, as this describes what values of the material are to be used and how these will be implemented in a new application. This design vision can be based on the needs and wishes of a target group, stakeholders or organisation, and/or the personal preference of the designer. It helps to guide the exploration for new applications, but can be iterated on as the exploration continues. For the exploration of suitable applications that are in line with the selected values and vision, ideation methods such as brainstorming, brainwriting, SCAMPER and mind-maps can be used [91]. Finally, selection methods such as the c-box, Harris profile or weighted objectives can be used to narrow down the ideas and select a final application for the material that is in line with the design vision.

A visual representation of the design framework is presented in Figure 7.2, where the source, processing, material characteristics, value selection, design vision and application are left open for the exploration. The diffuse boundaries between the three phases are shown through the fluid boundaries between the different parts, and the connected nature of the material aspects are demonstrated through the connecting lines. To show the use of the framework this project is used as a case study, as presented in Figure 7.3. For the first phase of the project the production process of thermoplastic parts for the aerospace industry is visualised, with the selection for the laminate off-cuts. The second phase shows the shaping and assembly possibilities that were explored the laminate off-cuts during the process, and visualises the geometry, appearance, mechanical properties and perception that were discovered as values of the material. The third phase visualises the selection of the material values, the design vision and the ideation process for finding suitable applications, with the final outcome of the bridge at the end of the process.

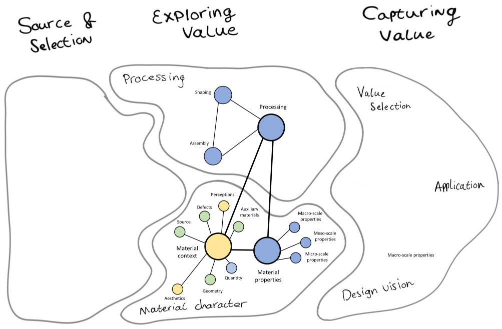


Figure 7.2: Visualisation of the outline of the design framework, with the aspects to explore the value highlighted

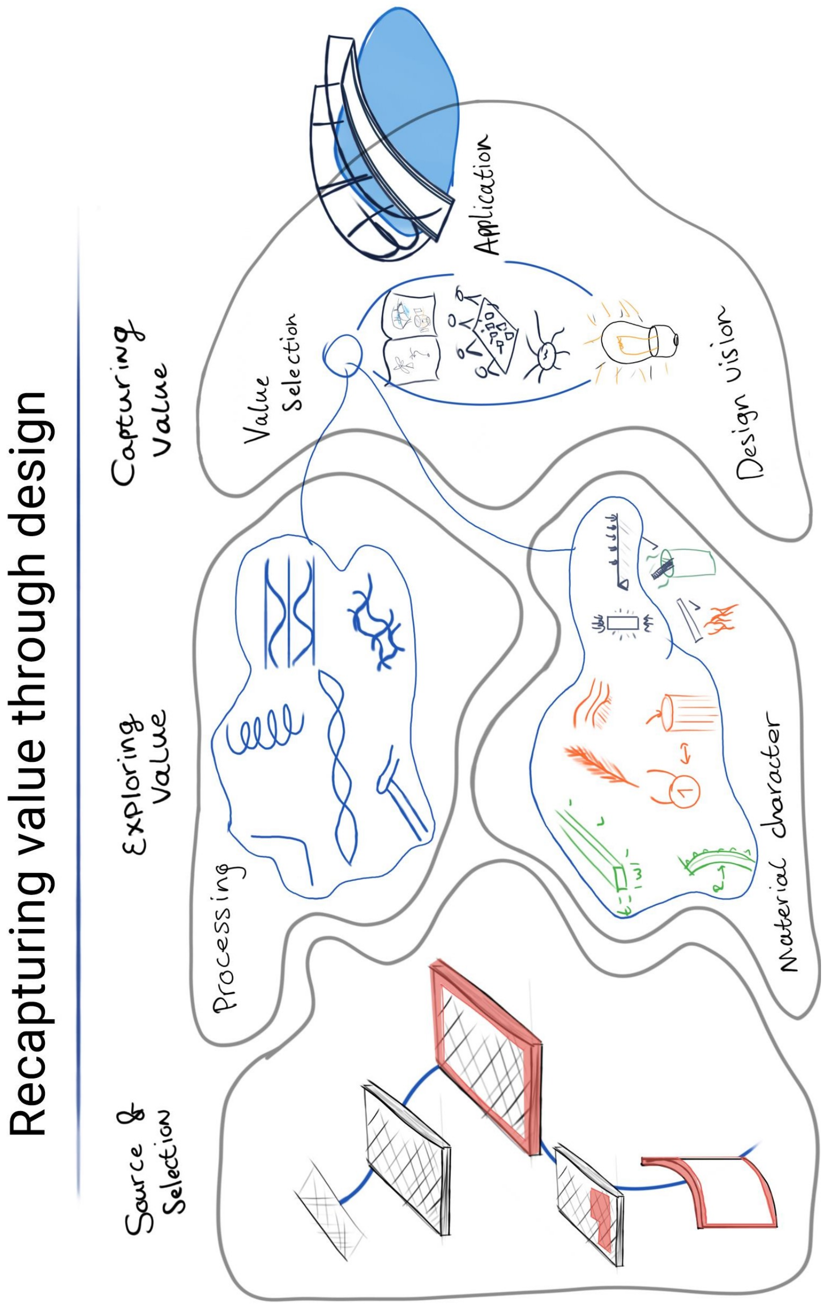


Figure 7.3: Illustration of the recapturing value through design framework. using this project as a case study

8 Conclusion

This chapter summarises the key findings of the report and answers the main research question formulated at the start of the project. Furthermore, it discusses the limitations of the project and presents recommendations for future work.

8.1. Project result

The main research question posed at the start of the project was as follows:

> How can designers and engineers design new applications from thermoplastic composite production waste?

To answer this question, the project followed focused on the use of one type of thermoplastic composite production waste: laminate off-cuts, and explored the use of the material in two design processes: one focused on a purely functional design, and one design that next to functionality, also includes a personality.

The design process focused on a functional design resulted in the design of a structural member, whose design can be tailored to a specific function. The shaping possibilities of the laminate off-cuts are utilised to to create a variable cross section for the structural member, which allows for tailoring of its properties. Through the construction of an analytical model, which captures the properties and failure modes of the structural member, the effect of varying the cross section of the structural member on its properties is demonstrated. To conclude this design, several design opportunities for the structural member made from laminate off-cuts are proposed. The design was evaluated according to its initial design criteria, which showed that it meets the criteria on a theoretical basis, but a dedicated design case and further analysis is required to validate its performance in practice.

The second design process resulted in a design that not only uses the mechanical properties of the material to fulfil a specific function, but also uses its aesthetic properties and perception to shape the personality of the design. This process resulted in the detailed design of a pedestrian bridge demonstrator, which aims to stimulate creative thinking about the use of the laminate off-cuts in new applications by design and engineering students. The mechanical properties and shaping possibilities of the laminate off-cuts are utilised in this design in the form of curved structural members, that are designed to carry the load of the pedestrians. The aesthetics of the material are used to give the bridge a modern and exclusive appearance, whilst utilising the shaping possibilities are utilised to create stiffening elements for the railing and to give the bridge a streamlined appearance. Additionally, the functionality of the defects present in the material, or those created during the shaping process, are demonstrated in the path over the deck of the bridge, and the railing, to indicate that these are also features that can be utilised. The design was evaluated with the target group according to its initial aim, which showed a positive response from the participants when asked if the final concept design helped them in the exploration of new applications.

By reflecting upon these two design processes, and discussing this with students that completed a similar project, insights on the design process with waste materials are gathered. These insights are used to create a design framework for designing with composite waste materials called: recapturing value through design. This framework consists of three phases, that provide structure and highlight key aspects within the process of designing new applications from composite waste materials. The process is illustrated through the use of this project as a case study.

These two design processes demonstrate that designers and engineers can utilise the laminate off-cuts in the design of purely functional products, but that their aesthetic properties and perception by the users can also be utilised to shape the personality of a product. Furthermore, the proposed design framework, recapturing value through design, provides a structure and key insights that designers and engineers can utilise during the process of designing new applications from composite waste materials.

8.2. Project limitations

The first limitation of the project is that the exploration of the mechanical properties of the laminate off-cuts was incomplete, and a conservative estimation on its mechanical properties had to be used. If the laminate off-cuts had been more closely examined for defects internally, in combination with mechanical testing, the mechanical properties of the material could have been more closely estimated and higher performance applications could have been examined for the material. Furthermore, information on the layup of the laminate off-cuts was estimated throughout the project, but could not be confirmed from the material manufacturer's side.

Secondly, the processing of the laminate off-cuts has only been explored on a prototype scale, and not completely according to the recommended processing parameters. Processing the material without adhering to the recommended processing parameters did reveal interesting insights into the processing, but also degraded the integrity of the material substantially in some cases. When processing the material according to the recommended parameters, the effect of shaping on the mechanical properties aesthetics of the material could have been investigated. This could potentially lead to new insights about the material that can be used in the generation of new applications.

Thirdly, the design of the structural member is only evaluated on a theoretical basis, making the design purely theoretical. The manufacturing and testing of a prototype of the structural member would have provided valuable information on its manufacturing feasibility and performance. Next to this, it would have provided the opportunity for the analytical model to be validated using mechanical testing data, adding additional functionality to the analytical model instead of just being a demonstration.

For the demonstrator bridge design, a limitation is that the final concept design could not be manufactured during the time of the project, which would have provided valuable insights into the manufacturing of the sections. Furthermore, this could have provided additional creative stimulation for the participants during the evaluation.

8.3. Recommendations

From this project, several recommendations can be made aimed at composite material manufacturers, and future academic work.

The first recommendation for material manufacturers is to keep track of the properties of the composite waste material, to ensure that this information is available for subsequent life-cycles. Without this information the use of the composite production waste material in structural applications is limited, as the properties will have to either determined through mechanical testing or conservative estimates will have to be used. Furthermore, it is recommended to keep the waste material to as close a state that is is created in, to ensure that the opportunities for re-use are retained.

One recommendation for future academic work is to create a method that can effectively estimate the mechanical properties of thermoplastic composite production waste material, by using information from the production process and the defects present in the material. Having a method that can estimate these properties could result in the adoption of the production waste material in high-end applications, preventing downcycling of the material.

Another recommendation for future academic work is to evaluate the proposed design framework for composite waste materials with design students, professionals working with composite waste materials, and with different composite waste material types. Performing this evaluation in more detail with a larger group can give more insights into designing new applications with composite waste materials, and open allow for wider implementation of this framework within the composites design/engineering sector.

9
Personal reflection

I started this project with the ambition to explore a more holistic approach to engineering and to apply this in a new field of study. The project allowed me to not only explore a functional design, but also allowed me to explore the experiential properties of the material and use them in a design process. Throughout the project my more analytical oriented mindset was challenged, forcing me to think more like a designers and less like an engineer. In the beginning of the project this was very difficult for me, as I was used to a more structured approach, and I found it hard to let go of this structure. However, I realised that to learn and expand my mindset, I had to let go of this structured approach and try something new. Within the design of the bridge demonstrator, I felt that I was really able to combine both the engineering mindset and a designer mindset. Through looking back at the beginning of the project and the result that I have currently, it became clear to me how my mindset shifted from an aerospace engineer towards a designer, ending up somewhere in between. Although there is still room for improvement, I noticed that by crossing the boundaries of my mindset into the unknown, broadened my mindset about engineering. I have learned new things about myself in terms of strengths and weaknesses, but also learned more about my interests in the field of civil engineering and architectural design.

Another learning ambition was to apply my prototyping and composite manufacturing knowledge in the manufacturing of a full-scale demonstrator. I thoroughly enjoyed prototyping with the thermoplastic composite material, and exploring how very simple processing methods can be used to explore the shaping possibilities of the material. I also found it an exciting process to explore how the defects created during manufacturing can actually be used as functional elements, and change the perception of the design. I think it was unfortunate that there was not enough time within the project to explore the manufacturing of a full-scale bridge demonstrator out of the material, as this would have resulted in new and interesting insights about the use of the material.

Another aim was to become more familiar with the concept of the circular economy, and the role that composites can play within this. At the beginning of the project I aimed to keep the integrity of the material as high as possible, to allow for high-grade re-use in next life-cycles. In later stages of the project I let this mindset go, and focused more on the final product that the material is used in, rather than maintaining the integrity of the material along the way. This released some of the internal restrictions that I had about shaping the material, and allowed me to better explore the possibilities for high-grade re-use of the material in new applications.

Finally, I would like to reflect on the process of initiating this thesis project and the approach that I used. The initiation of this combined thesis project, and the administrative tasks that come with this, was not an easy undertaking, and required extensive thought about a process that I did not feel comfortable with at the time. As the project progressed, I became more aware of the process that I was following and gained confidence as the first results of the process emerged. I look back on this process as being frustrating and difficult at times, but also as being a great learning opportunity that allowed me to explore past the boundaries of my mindset and capabilities.

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A
Project Approach

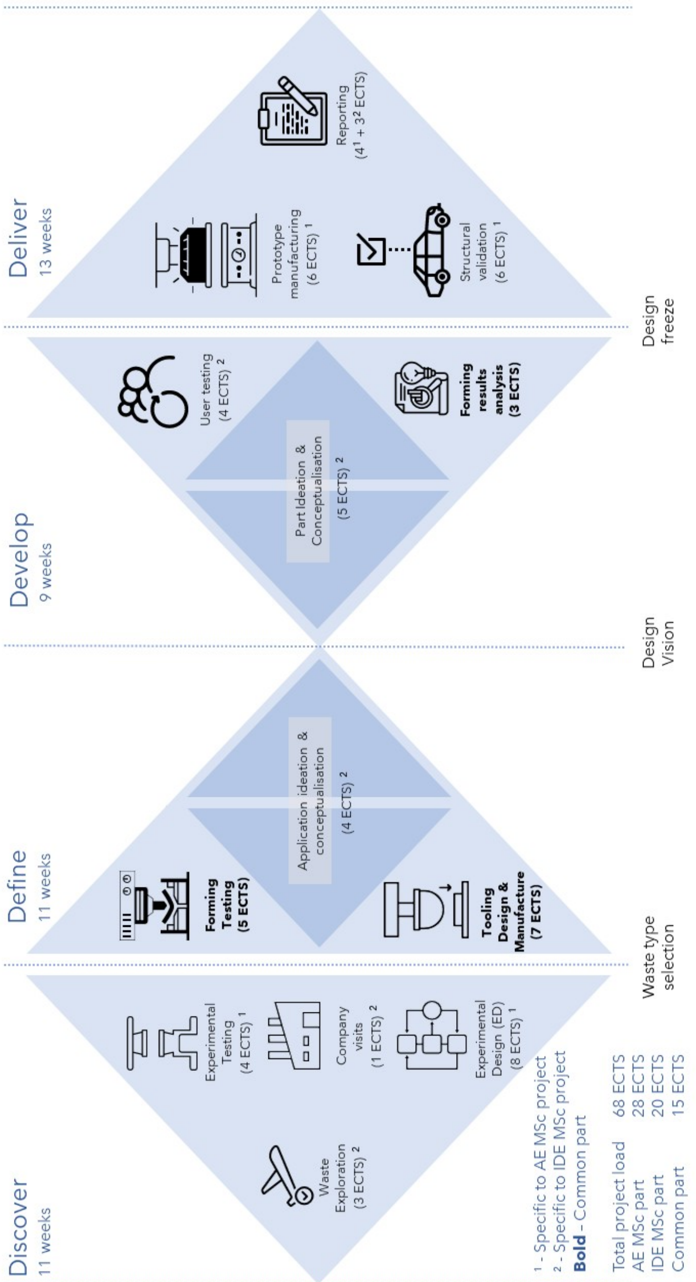


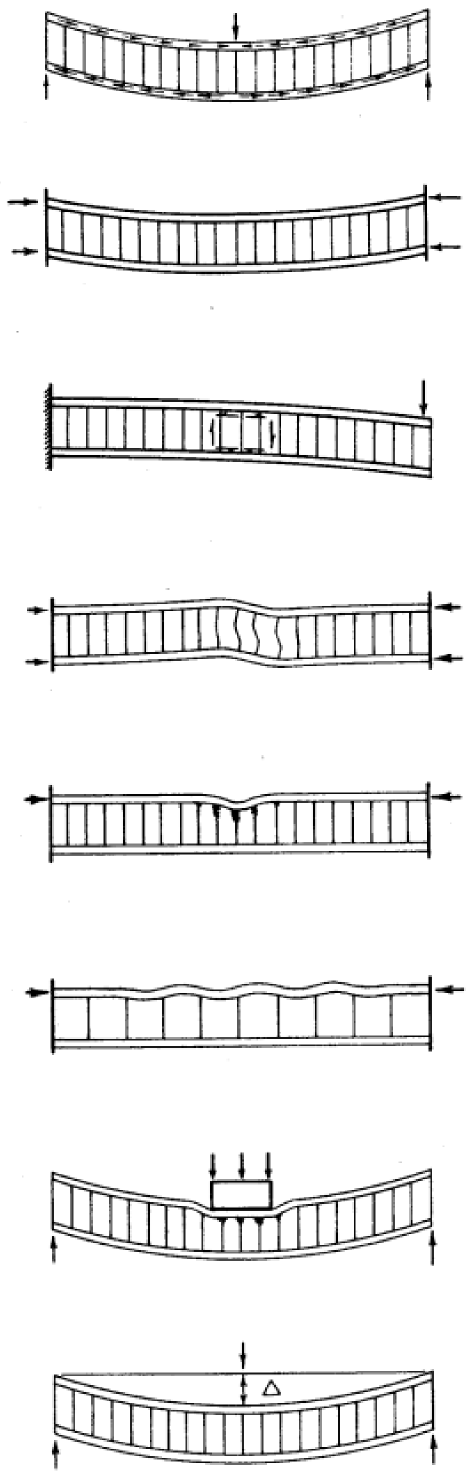
Figure A.1: Figure detailing the different phases of the project, and the activities within

B
Sandwich composite failure modes

DESIGN REQUIREMENTS, MODES OF LOADING AND FATIGUE

Sandwich structures should be designed to meet the basic structural criteria listed below when these criteria pertain to the type of loading under consideration.

FIGURE 3



1) The facings should be thick enough to withstand the tensile, compressive, and shear stresses induced by the design load.

2) The core should have sufficient strength to withstand the shear stresses induced by the design loads. Adhesive must have sufficient strength to carry shear stress into core.

3) The core should be thick enough and have sufficient shear modulus to prevent overall buckling of the sandwich under load, and to prevent crimping.

4) Compressive modulus of the core and the compressive modulus of the facings should be sufficient to prevent wrinkling of the faces under design load.

5) The core cells should be small enough to prevent intra-cell dimpling of the facings under design load.

6) The core should have sufficient compressive strength to resist crushing by design loads acting normal to the panel facings or by compressive stresses induced through flexure.

7) The sandwich structure should have sufficient flexural and shear rigidity to prevent excessive deflections under design load.

Figure B.1: Summary of the failure modes under different loading conditions for sandwich composite materials [130]

C
Sandwich composite analysis

SANDWICH DESIGN (continued)

ANALYSIS OF FLAT RECTANGULAR SANDWICH BEAMS

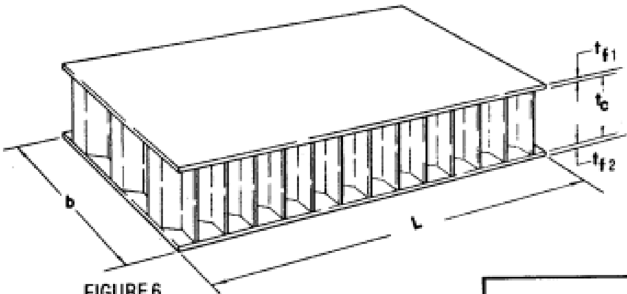


FIGURE 6

$$h = \frac{t_{f1}}{2} + \frac{t_{f2}}{2} + t_c$$

FIGURE 7
BEAM CHART

BEAM TYPE	MAXIMUM SHEAR FORCE V	MAXIMUM BENDING MOMENT M	BENDING DEFLECTION CONSTANT K_b	SHEAR DEFLECTION CONSTANT K_s
SIMPLE SUPPORT, UNIFORM LOAD, P = ql	0.5P	0.125PL	0.01302	0.125
BOTH ENDS FIXED, UNIFORM LOAD, P = ql	0.5P	.08333PL	.002604	0.125
SIMPLE SUPPORT, CENTER LOAD, P	0.5P	0.25PL	0.02083	0.25
BOTH ENDS FIXED, CENTER LOAD, P	0.5P	0.125PL	.00521	0.25
CANTILEVER, UNIFORM LOAD, P = ql	P	0.5PL	0.125	0.5
CANTILEVER, END LOAD, P	P	PL	0.3333	1
CANTILEVER, TRIANGULAR LOAD, P = ½ql, q	P	0.3333PL	0.06666	0.3333
ONE END SIMPLY SUPPORTED, ONE END FIXED, UNIFORM LOAD, P = ql, q	0.625P	0.125PL	0.005405	.07042

*If deflections are critical, actual deflections should be verified by tests.

BENDING STRESS IN FACINGS

$$\sigma_{fi} = \frac{M}{t_{fi} h b} \quad i = 1 \text{ or } 2$$

where M is determined by Figure 7

CORE SHEAR STRESS

$$\tau_c = \frac{V}{hb}$$

V is from Figure 7

DEFLECTION K_b and K_s from Figure 7

$$\Delta = \frac{2K_b P L^3 \lambda}{E_f t_f h^2 b} + \frac{K_s P L}{h G_c b} \quad \text{(for same skin materials)}$$

or

$$\Delta = \frac{K_b P L^3}{D} + \frac{K_s P L}{h G_c b} \quad \text{(see D below)}$$

(For most long beams, the second term is relatively small, but should be checked if deflection is critical.)

FACE DIMPLING

$$\sigma_{CR} = \frac{2E_f}{\lambda}\left[\frac{t_f}{s}\right]^2$$

FACE WRINKLING

$$\sigma_{CR} = 0.82\,E_f\left[\frac{E_c t_f}{E_f t_c}\right]^{1/2}$$

$$D = \frac{E_1 t_1 E_2 t_2 h^2 b}{E_1 t_1 \lambda_2 + E_2 t_2 \lambda_1} \quad \text{or} \quad \frac{E t_1 t_2 h^2 b}{(t_1 + t_2)\lambda} \quad \text{or} \quad \frac{E t h^2 b}{2\lambda}$$

LIST OF TERMS

P = Total Load	Δ = Deflection	$\lambda = 1 - \mu^2$
L = Span	E_f = Facing Modulus	μ = Facing Poisson's Ratio
σ_f = Facing Stress	G_c = Core Shear Modulus	S = Cell Size
t_f = Skin Thickness	b = Width	E_c = Core Compression Modulus
h = Centroid Distance	σ_{CR} = Critical Facing Stress	t_c = Core Thickness
τ_c = Core Shear Stress	D = Panel Stiffness	I = Moment of Inertia

Figure C.1: Summary of the analysis of the stresses present in the face sheets and core material, deflection of the material and local failure modes[130]

D
Specification of production waste types

	Material properties	Manufacturing Processes	Source	Design freedom	Main Insights
1) Single prepreg layers	**Mechanical Properties** High mechanical properties per ply **Defects** unconfirmed fibre/matrix volume ratio, split tape along length **Geometry** The widths may range from 1/5" to 12" (5mm to 300mm), lengths can be 10cm to 10m. Thickness around 0.15mm	• Hand layup/automated pick and place • Compression moulding • Autoclave consolidation • Thermoforming Rapid automated manufacturing methods such as AFP or ATL are not possible due to the irregular shape and size of the materials	**Tape manufacturing** Non-conforming sections due to matrix/fibre defects **Tape laying** Cut-offs due to minimum tape length and extra length outside of laminate	**Layup** Large freedom due to single ply, can be stacked into a tessellated laminate with any orientation. **Shape** Large shaping freedom: as a stacked laminate it can be shaped into single curved or double curved shapes within some processing boundaries	+ Large design freedom + large amount available from manufacturers - Time consuming to stack into laminate - Tessellated structure is not consistent for each laminate created
2) Laminate cut-offs	**Mechanical Properties** High mechanical properties, aligned layup structure, contains continuous fibers. **Defects** include resin flow out, misaligned fibers due to transverse flow and woven fabric ends (nylon wire). **Geometry** Flat, thickness 1-5mm, length up to 3600mm and widths from 5-15mm	• Automated pick and place • Compression moulding • Including overmoulding • Autoclave consolidation • Thermoforming • Localised press forming Rapid automated manufacturing methods such as AFP or ATL are not suitable as material is consolidated	**Consolidated laminate trimming** Large laminates are manufactured at the material suppliers, for direct use by the material processers. Each of these laminates is trimmed to take off any defects that may occur on the edges of the laminate.	**Layup** Limited, placement of extra plies is possible through extra consolidation, or sections can be stacked to double the layup. **Shape** Mostly single curvature shaping due to the lack of width of the sections and the long length. Joining of the sections is possible through localized welding	+ Consistent supply of material + Large amount available + Continuous fibers present + Long section length - Shaping limited to single curvature bending & joining - Possible defects due to edge effects during consolidation - Varying materials & layup for each section
3) Blank cutting remains	**Mechanical Properties** High mechanical properties, aligned layup structure, contains continuous fibers. **Defects** Possible fibre tear out near cutting regions **Geometry** Flat, thickness 1-5mm, larger sections (50x3600mm) near the edges or smaller sections from between cut parts	• Automated pick and place • Compression moulding • Including overmoulding • Autoclave consolidation • Thermoforming • Press forming Rapid automated manufacturing methods such as AFP or ATL are not suitable as material is consolidated	**Nested blank cutting** Nestes blanks are cut from a larger section of material (generally 1200x3600mm) leaving material around the blanks (minimum spacing 5mm) and around the edges of the laminate (25mm minimum)	**Layup** Extra plies can be added to the existing layup for larger sections, and sections can be combined to double the layup **Shape** Single and double curvature bending is possible for the larger sections, and sections can be joined through formed flanges or edges	+ Consistent supply of material + Large amount available + Continuous fibers present + Long section length + Larger sections available - Dependent on part geometry & production - Can be minimised through production optimisation - Varying materials & layup for each section
4) Post-forming trim-offs	**Mechanical Properties** High mechanical properties, aligned continuous fibres present **Defects** Fibre tear out near cutting regions, contains insulation material & coatings, and drilled holes for alignment **Geometry** Bent, thickness 1-5mm, small width (15-25 mm), follows contour of part made	• Thermoforming • Press forming Most processes are not suitable for this material as it is bent and would require dedicated tooling for consolidation	**Formed part edge trimming** In the process of trimming the composite part to its final dimensions, the edge aids in the alignment and clamping of the part during processing. After the entire contour of the part has been trimmed, the outer part edge remains as waste material.	**Layup** Limited options for adding plies due to the inconsistend geometry of the parts, similar parts could be stacked to from larger thick sections **Shape** Part will have single curvature present, which can be reversed or increased to form a new geometry.	+ Consistent supply of material + Large amount available + Continuous fibers present - Geometry dependent on part - Many holes/defects present - Limited shaping possibilities
5) Milling remains	**Mechanical Properties** Low, small length carbon fibres in non-pure waste stream **Defects** short fibre length, parts of insulation material and coating present **Geometry** Single digit millimeter range of fibre length	• Compression moulding • Including overmoulding The only processing step at this point is compression mouldig, but this would require a pure waste stream: only polymer and fibre.	**Final part milling** In the process of trimming the composite part to its final dimensions, material is removed between the edge of the component and the outer trimming edge, using a milling tool. This milling tool shreds the fibres and leaves behind a mixture of the materials present in the part: Carbon fibres, the polymer, the insulation material and the coating.	**Layup** Orientation of the individual fibres can be tweaked through the processing parameters, forcing flow in one direction would align the fibres in this direction as well. **Shape** using compression moulding complex features can be made on top of larger curved thinner sections.	+ Consistent supply of material + Large amount available - Limited mechanical properties - Complex & expensive processing - Waste stream contaminated with insulation & coating material

Figure D.1: Specification of five different types of waste identified in the forming process of thermoplastic composite parts

E

Thermoplastic composite strip - single ply off-cut press forming experiment

This single experimental testing plan was made explore the press forming of a laminate made from single ply off-cuts, in the applied labs at the faculty of Industrial Design Engineering. The testing plan details the method used durign the experiment, presents the results and makes conclusions from these.

Heated press experiment Material Lab IDE

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Introduction

Within my graduation topic I am exploring the applications of thermoplastic composite production waste from the aerospace industry. One of these types of waste material is UD (Uni-Directional) tape consisting of carbon fibres and thermoplastic resin. I am interested in whether this material can be processed using the heated press in the materials lab, which could be the starting point of further more controlled experiments.

Materials & Tooling

For this experiment I will be using UD carbon fibre tape, reinforced with the Toray Cetex 1225 thermoplastic resin. This thermoplastic resin has a melting temperature of 305 °C, and a processing temperature of 340 °C. The material safety datasheet and the product datasheet are also supplied with the accompanying email. The decomposition temperature of the material is 450 °C, which is higher than the processing temperature during this experiment. As such, no hazardous or toxic fumes are expected during the processing.

For the pressing of a stacked laminate, almost no tooling would be required except for two release films on the top and the bottom of the laminate. As I would also like to test manufacturing with flakes of material, this would require a border around the material to prevent it from shifting, some tooling is proposed for this test as well. The tooling is partially available at the heated press station,

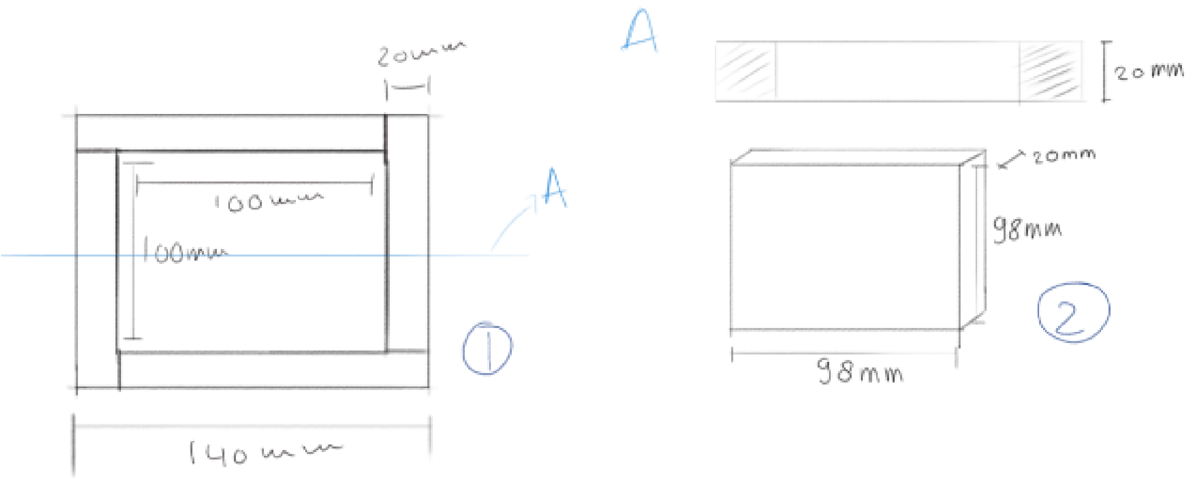


Figure 1 Outer (1) and inner mould (2) for the experiment

and consists of two components, the outer mould and inner mould. The outer mould is a rectangle created from 4 square pieces of aluminium, and the inner mould is a square made out of aluminium as well. The dimensions of these are shown in Figure 1.

All surfaces that will come into contact with the moulding material will be covered with Kapton film to prevent adhesion. This is a Polyimide film that is temperature resistant up to 400 °C.

If available, thermocouples can be placed on the mould or within the laminate to have a direct temperature reading, which would save time for the pressing. The temperature of the top pressing block and the bottom of the laminate should be 340 °C before applying pressure.

Process

The proposed manufacturing process is partially illustrated in Figure and 3, and will follow the predefined steps:

1. Placement of the outer mould on the pressing plates
2. Placement of the pre-stacked laminate inside the outer mould
3. Placement of the inner mould on top of the laminate
4. Pressure is applied until the heated top pressing plate is in contact with the laminate (up to 1-2 bar of pressure)
5. Heating to 340 °C
6. Increasing of the pressure up to 5 bars
7. Dwell for 30 minutes
8. Initiate cooling whilst maintaining the pressure
9. Release the pressure when temperature of the pressing plates reaches below 100 °C
10. Removal of the mould when the temperature reaches 40 °C.

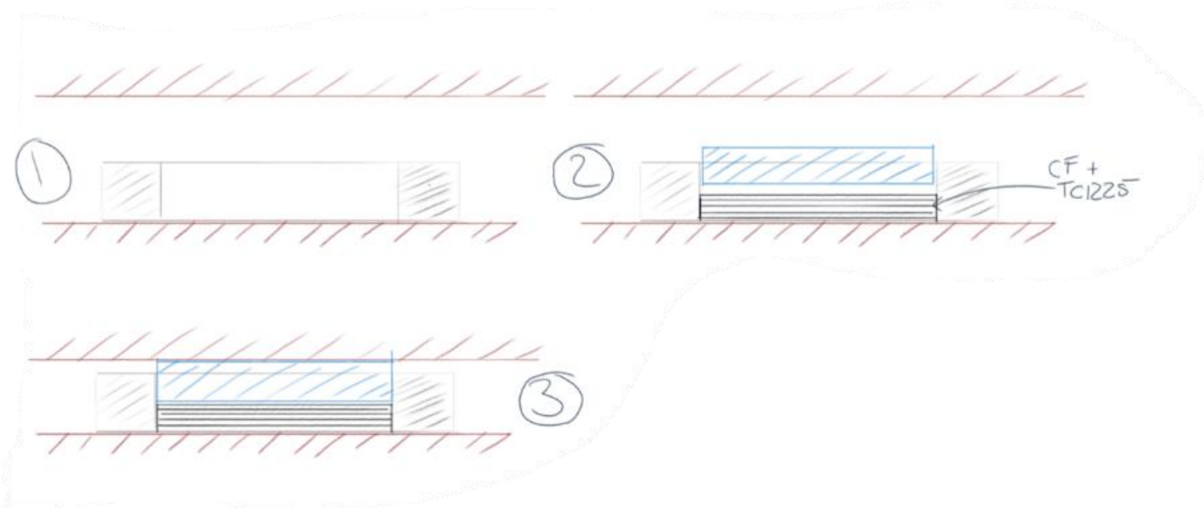


Figure 2 (1) Placement of the outer mould on the pressing plates (2) placement of the UD tape material (3) lowering of the top pressing plate onto the UD tape material

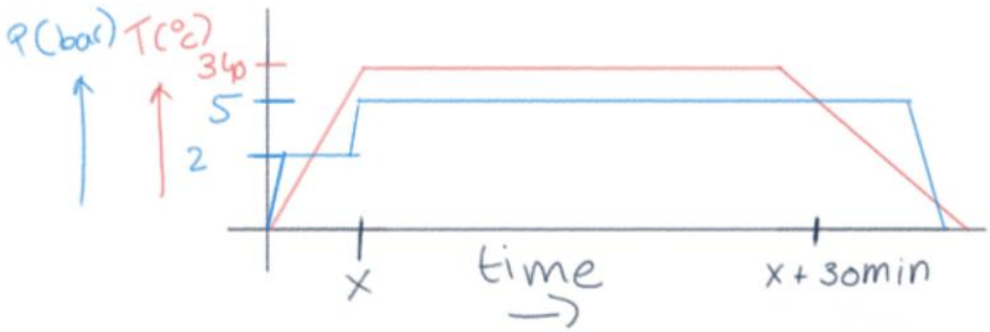


Figure 3 Temperature and pressure profile during the length of the manufacturing process

Results

The resulting sample from the forming experiment are presented in this chapter. The quality of the formed samples is low as they show a large amount of porosity, and voids on the surface. Furthermore, sliding of the material during the heated press forming was observed, which is also present in the sample. The process also showed that it was very resource intensive to obtain a multiply laminate from the use of single ply off-cuts, as these has to be trimmed to fit in the small mould.

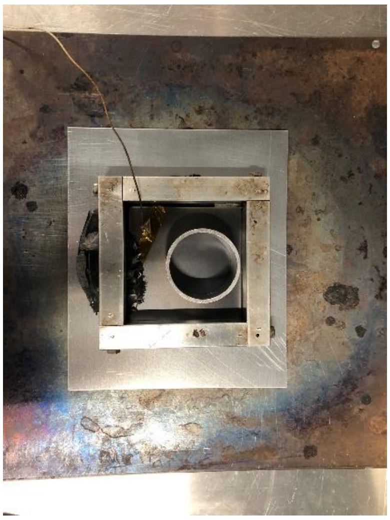


Figure 4 Sample after the pressing with the moulds still present

Figure 3 Sample after pressing with the mould removed, showing signs that the material shifted during processing

Figure 2 Sample as it is presented for closer inspection using the microscope

Figure 5 Image taken from the microscope of the surface of the sample, demonstrating severe porosity

Figure 7 Single ply off-cuts laid out before trimming

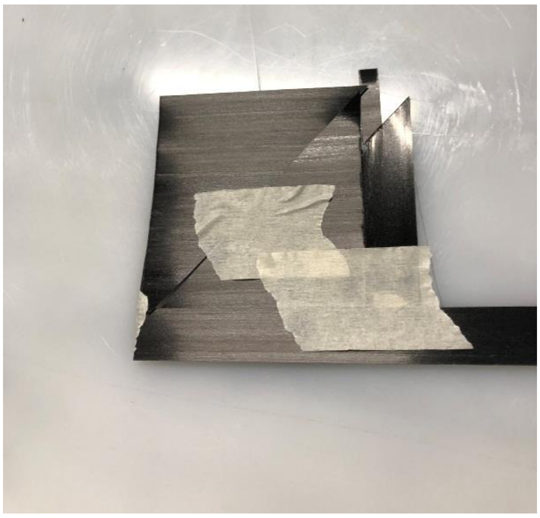


Figure 6 Trimmed sections of the single ply off-cuts into the square mould shape, tied together using a tape to maintain their alignment during further processing

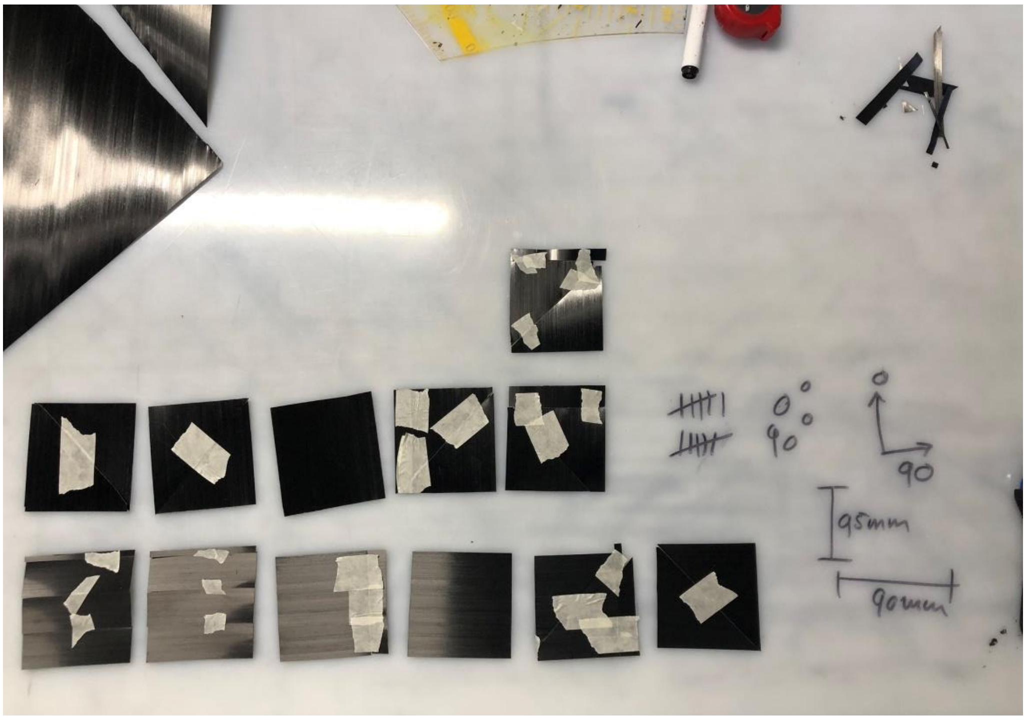


Figure 8 Presentation of all the layers to be used for the press forming experiment

Conclusion

The conclusion of this test is that the processing of single ply off-cuts required specialised tooling and will take too much resourced in this phase of the project. As such, it is recommended that the single ply off-cuts are not used for the remainder of this project.

F
Laminate off-cut defect inspection

Figure F.1: Close-up of the dry spot caused by a possible alignment pin, with thermal degradation and resin-squeeze out present

Figure F.2: Thermal degradation of the edges of the laminate off-cut resulting in delamination

Figure F.3: Foreign material contaminants on the outside of the material, in this case PI tape (kapton) and a piece of paper

Figure F.4: Clamped end of the laminate off-cut to determine the in-plane warpage

Figure F.5: Other end of the clamped laminate off-cut with the measurement of the in-plane warpage over its length

Table F.1: Defects found as a result of a visual inspection of the laminate off-cuts

Defect	Description	Cause	Effect on properties
Thermal degradation	Darker resin spots at the edges of the laminates, see Figure F.2	Temperature higher than the degradation temperature during consolidation [12]	Degradation of the polymer, possible increase of Tg, formation of matrix cracks and voids at the exposed area leading to a reduction in elastic modulus, weakening the fibre/matrix interface and causing delamination [131],[132] [133]
Resin squeeze out	Resin squeezed out the edges of the laminate	Low viscosity of the resin material due to a high temperature, and a high pressure applied for consolidation	Increase in fibre volume fraction due to lower resin content i.e. resin starved areas, reduction in thickness, possible internal dry fibres reducing the matrix dominated properties such as compression, shear strength and delamination fracture toughness [12][133]
Foreign material contamination	Contamination of the material with foreign materials used in processing – PI tape and paper, see Figure F.3	Tape can be used for blank holding during processing, paper used for identification purposes	No apparent effects as these are present on outside of material
Dry spots	Round spot 5mm diameter with less resin present compared to surrounding areas, and fibre misalignment inside and around the spot, seeFigure F.1	Possible pin used for alignment of the blank in the consolidation press, creating a compaction pressure than surrounding areas and restricting the flow in and around this pin	Similar as mentioned for the resin-squeeze out, more local and on the surface of the laminate allowing for exposure to moisture or chemicals – potential damage initiation site to load bearing fibres [133]. Misalignment can lead to a reduction in strength and modulus in the fibre direction [12]
Material warpage	In-plane warpage observed in the laminate off-cuts with a smaller width, possible caused by residual stresses during cooling	In-plane warpage results in dimensional inaccuracy of the final part, and causes fibre misalignment that can adversely affect the material properties in the direction of the warped fibre [12].	

G
Processing parameters literature review

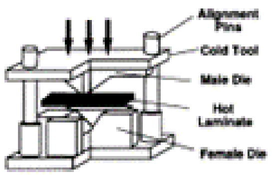
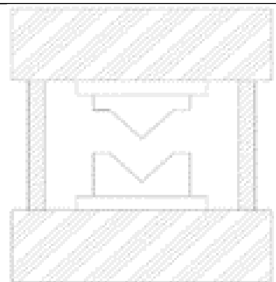
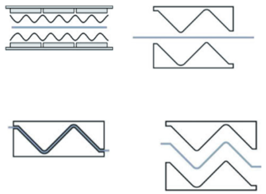
Table G.1: Overview of literature reviewed on the processing parameters of single bend forming with constrained and unconstrained boundary conditions

Reference	Material thickness	Radius / Thickness	Bend angles	Processing conditions	Defects observed	Effect on mechanical properties
[134]	1. CF/PP, 2.8-3.0mm 2. CF/PA12, 3.0mm 3. CF/PEEK, 3.0mm 4. GF/PEI, 2.5, 3,85 & 5.0 mm	R/t=0.833 for CF laminates	90°	Heating conditions: CF/PP = >160°C CF/PA12 = 220°C CF/PEEK = 385°C GF/PEI = 280°C Forming speeds: CF/PP = >200 mm/min CF/PA12 = 200-500 mm/min CF/PEEK = 200-500mm/min GF/PEI = >300mm/min Switch off stamping pressure = 1.17 – 2.90 MPa	Bending or breaking of fibres at low stamping velocities At high velocities (and pressures) excessive thinning of the bend sides & resin migration out of the laminate, causing a thickness reduction	
[77]	1. UD PA6/CF - 0.6mm	R/t = 8.33	90°	Blank locally heated outside of mould varying between 220°-260°C (Tm = ~220C) Varying locally heated range from 10-20mm Forming speed of 1520mm/sec Applied pressure between 0.49 – 0.78 MPa	Fibre buckling on inside corner at temperatures lower than 260°C, delamination also present. Above 260° C only wrinkles and no delamination or fibre buckling.	Mechanical properties of locally heated sample at 260°C with wrinkles are comparable to fully heated sample under bend opening loading

[78]	1. CF/PPS [0,90]4 – 1.24mm 2. CF/PPS [0,90/±45]S – 1.24mm 3. CF/PPS [(0,90/±45)2/(0,90)]S – 3.10mm	T1: R/t = 2&3 T2: R/t = 4&5 T3: R/t = 2&4	90°	Blank preheat temperature at 330°C Varying tool temperature from 180°-220°C Forming speed of 32mm/sec Varying pressure from 2.2-5.5 MPa	Thickness reduction, resin migration and increased voids after bend sections.	Minimum stamping pressure of 3.3MPa and radius/thickness ratio of 3 is identified for optimal Curved Beam Strength (CBS) for 5-HS satin weave CF/PPS samples
[73]	1.CF/PEEK [0/45/90/-45]3s – 3.4mm 2.CF/PEEK [02/452/902/-452/0/45/90/-45]s – 3.4mm 3.CF/PEEK [03/453/903/-453]S – 3.4mm	R/t = 2 @ 90° R/t=2.35 @ 105° R/t=2.85 @ 120°	90°, 105° 120°	Blank heated to 390°C @ midplane and tool at 240°C Forming speed N.D. formed under 20 bar (2MPa) of pressure	Fibre waviness (in reverse formed samples)	N.A Increased fibre waviness for smaller formed bend angles
[76]	1.QI CF/PA6 -1.0mm	R/t = 5	90°	Blank heated in mould in two conditions: 1.Upper laminate/Lower Laminate = 230°C/230°C 2.Upper laminate/Lower Laminate = 200°C/260°C Forming speed 15mm/s & 0.1mm/s 1 MPa of pressure applied	1.Delamination after the bend sections and in-plane waviness of the fibres on the inside of the bend 2.Reduced delamination after the bend, but increased in-plane waviness on the inside of the bend	Increased rigidity of the bend section under angle opening loading condition for heating condition 1

H
Review on stamp forming and single bend forming equipment

Table H.1: Overview of the processing equipment used to form single bends in selected literature

Reference	Process description	Illustration	Tooling description	Temperature control	Pressure application	Blank holding
[134]	Samples are heated outside the tooling, then formed using cold matched die tooling		Male – female matched dies with specified distance between the two mould haves. No defined displacement stop	**Sample** Conduction heating using two heated platens to above melting temperature **Tooling** Room temperature	Universal testing machine Zwick 1474, under compression mode	Sandwiched between two Kapton 200HN foils
[77]	Samples are heated outside the tooling through an IR strip heater and formed using the cold matched die tooling		Male – female matched dies	**Sample** Infrared strip heated with variable heating range **Tooling** Room temperature	Press (limited to 0.49-0.78 MPa)	N.D.
[78]	Samples fully heated in an IR oven outside of the tooling, and formed using a set of heated S shaped matched tools		Three sets of matched set of S shaped tools, different radii for two corners in the mould are used	**Sample** Heating in infrared oven prior to forming **Tooling** Controlled from 180-220°C	150 ton hydraulic press (V150H-36-CX, Wabash), pressure during test varied from 2.2-5.5 MPa	Sandwiched between Kapton films and retained in tension by a steel frame
[73]	Samples heated in an IR oven, and formed using a set of matched die tools with varying bend angles, and reverse forming using flat plates		Three sets of matched die tools with 90°, 105° and 120° degree bend angles, a and 6.4, 8 and 10mm radius.	**Sample** heating in IR oven outside mould to 390°C **Tool** Controlled and kept at 240°C	Press, 40 bar pressure for forming	Toggle clamps as blank holder

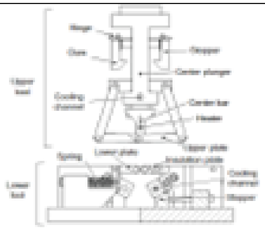
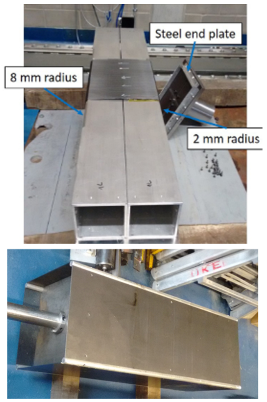
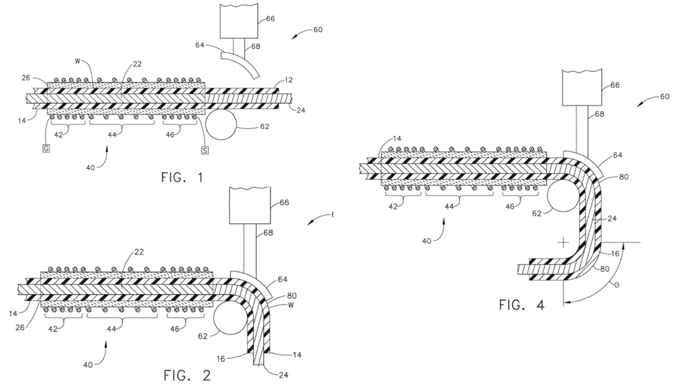
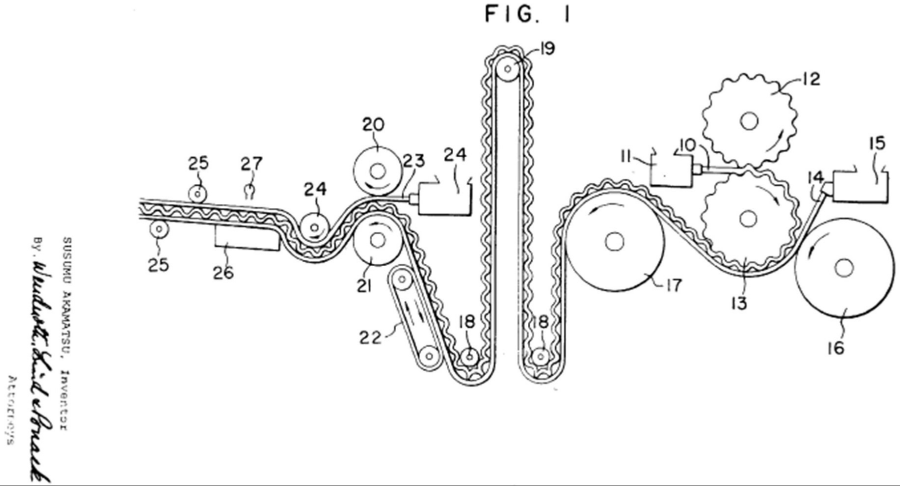
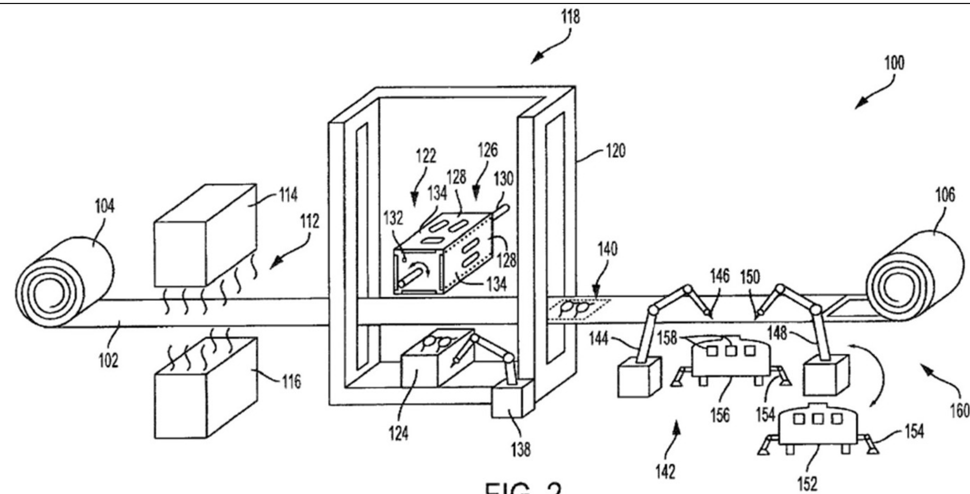
[76]	Press-brake like process, where the samples are heated inside the tooling, and are formed to a specific angle		Upper tool with a heater, center bar and rod at the radius to be formed, covered by a stainless steel skin acting as a layer to apply pressure. Lower tool with spring loaded stopper and flexible stainless steel skin.	**Sample** Heated inside the tooling from top & bottom by 3 different heaters (conduction based) **Tooling** Stainless steel skins are heated together with the laminate	Through center rod, surfaces that the load is acting upon are the stainless steel skins, the upper plate and the lower plates	Blank is held in between two stainless steel skins (0.03mm thickness). No further specification is made on the placement of the blanks
[79]	Laser assisted automated fibre placement over rotational mould with varying corner radii		Rectangular mould with four different corners of varying radii	**Sample** layers are heated with the laser **Tooling** Tooling is kept at room temperature	Applied through a conformable silicone roller with pneumatic pressure of 2.5 bar/0.25 MPa	Tapes are held under tension through the automated tape laying rollers

Table H.2: Overview of the processing equipment found in patents and through company visits to form single bends

Patent Company	Process description	Illustration
EP3208068B [135]	Heating of the thermoplastic composite tube using the induction heating elements (22,26), after which the tube is positioned in front of the anvil (62). The hammer (64) is brought to the anvil (62) and the bend is formed.	
US3682736 [136]	Method of manufacturing a continous sandwich beam with a corrugates core material our of cardboard	

ES2826377T3 [137]	Method of forming bends in a thermoplastic composite material using a conveyor belt system with adapable mould geomnetry. The mould geometry is adaptable through rotation of the mould, with each different radii on each corner	 FIG. 2

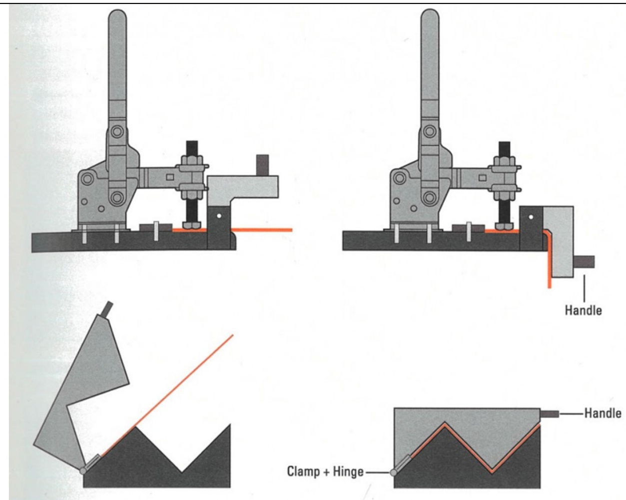
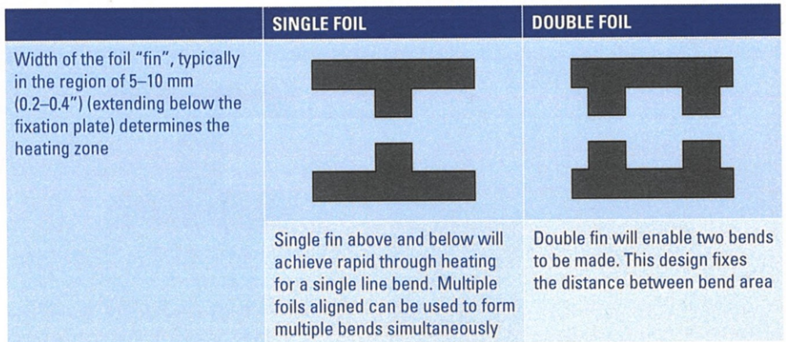
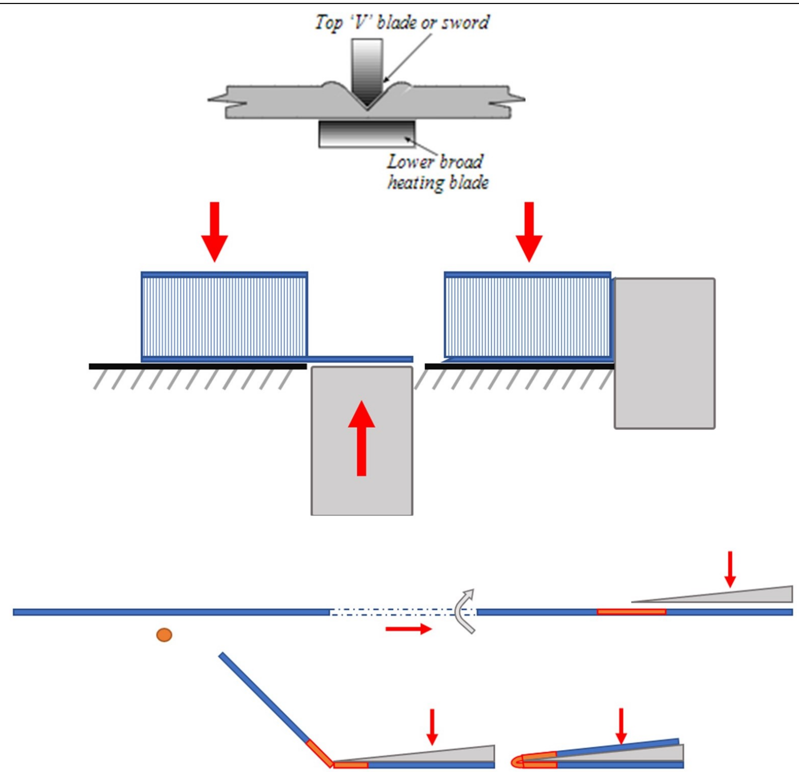
Toray Advanced composites [61]	Samples are held on one side using toggle clamps and formed using matched die tooling with handles. These moulds are generally out of prototyping materials (wood, plastic) and are non-heated. Heating is done locally using line heaters, which heat up the laminate locally through conduction heating.	

Figure 18. Simple tooling enables rapid part location and forming



Aerospace manufacturing companies & Clarke [138]	Two different mechanisms are used for single bend folding, a mechanism using a contact heater and a "hammer" mechanism, and another using wire heating and a matched die folding mechanism. The first mechanism uses a 'knife' to locally heat the laminate, and a hammer is moved upwards to form a locally heated sheet around a 90° bend. The second process uses heated wires to locally heat the material from the bottom side. When the processing temperature is reached, the material is shifted to another location where the bending step using the matched tooling takes place.	

I
Strip form selection details

Criteria	--	-	+	++
C-FS-1 Adaptable to material	The form offers no possibilities of compensating for variation in material properties	The form offers one method to compensate for variation in the material properties, but limits the design freedom	The form offers a method to compensate for variation in the material properties, and does not limit the design freedom	The form offers multiple methods to compensate for a variation in the material properties and does not limit the design freedom
C-FS-2 Ease of manufacturing	The process requires extensive tooling, that is not commonly used, with a complex assembly process to realise a high-quality shape	The manufacturing process requires moderately complex tooling, with a straightforward manufacturing process to realise a high-quality shape	The manufacturing process requires commonly used tooling, with a straightforward manufacturing process to realise a high-quality shape	The manufacturing process requires commonly used tooling, straightforward assembly methods, and can be easily adapted to large scale manufacturing of high-quality parts
C-FS-3 Structural performance	The form does not offer the possibility of maximising the strength, stiffness or weight of the structure	The form offers a possibility for a high strength, stiffness or low weight, but is not efficient in material usage	The form can be adapted for a high strength, stiffness or low weight, and is efficient in material usage	The form can be adapted for a high strength, stiffness or low weight, is efficient in material usage, and can be easily implemented in a design process
C-FS-4 Adaptable functions	The form cannot be used to fulfil another function, even through extensive reprocessing	The form can be used to fulfil some specific functions after extensive reprocessing	The form can be used to fulfil multiple functions after limited reprocessing	The form can be used to fulfil a wide range of functionalities without reprocessing

Figure I.1: Specification of the different levels of the criteria used in the Harris profile for the structural form selection

Criteria	Coiling	Twist & bending	Weaving	Corrugated sandwich
C-FS-1 Adaptable to material	(-) Thickness compensation is possible through stacking of strips, varying width does limit the design freedom through the winding angle (restricts the possible height that can be traversed through a single winding)	(+) Variation of the cross section due to changing thickness and width can be done through stacking of the strips, and does not influence the design freedom of the shape	(++) Variation of cross section due to changing thickness and width can be done on a “weaving strip” level through stacking of strips, or compensation through another weaving strip.	(++) Variation of cross section due to varying thickness or width is possible through stacking of strips, both in the face sheets (bottom and top), or in the corrugation pattern.
C-FS-2 Ease of manufacturing	(--) requires complex tooling that is adapted to the cylindrical shape of the material, rotates to heat the strip and places the strip along the cylinder.	(-) Twisting requires complex too to apply the compaction to the material, single bend forming uses common tooling	(-) Single bend forming tooling is used to create the bends for weaving, assembly is complex to do with the shaped strips due to the order of attachment.	(+) only required common single bend forming tooling, and straightforward tooling for attachment.
C-FS-3 Structural performance	(+) The shape of the coil can be optimised, as well as the cross section of the to be coiled material, and which efficiently uses the material.	(+) Through bending the material can be put where it offers maximum benefit for the properties, without requiring additional material. Twisting of the strip performs the same and increases the dimensions in which these properties are present.	(-) The structure can be adapted for a high-performance but is not efficient with the use of material, through its woven nature.	(+) The form allows for placing the material at the right location for maximum structural properties, and offers multiple places to do so
C-FS-4 Adaptable functions	(-) The form can be used as an aesthetic element in next lifecycles, which can be possible through small modifications, but requires extensive reprocessing to make other applications possible	(+) The form can be adapted to different functions through re-shaping, but remains limited in scope	(+) The form can be adapted for new functions through re-shaping, but with a limited scope	(++) The shape can already by used in the same functionality as the shape is in the form of a standard structural element, but its performance might be less.

Figure I.2: Reasoning behind the ratings given to each criteria for the four forms

J
Thermoplastic composite strip - single bend forming experiment

This single bend testing plan was made for the employees of the DASML testing lab at the faculty of Aerospace Engineering, to obtain approval for the test, and documents the method used, the results, a discussion on the results and conclusions drawn from the experiment.

DASML- TP composite bend forming

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Introduction

Within my project I am looking at the shaping of thermoplastic laminate off-cuts, long slender strips, into a corrugated pattern. This pattern is used as a core material within two strips to make a sandwich beam structure, as illustrated in Figure 1. I would like to try two different methods of forming bends in these strips: by using a heated tool (above matrix Tm) to heat the material and form it simultaneously, and one by using a heated tool (below matrix Tg) and heating the material above the melting temperature separately. A graphical representation of this is shown in Figure 2. Through this test I would like to explore which forming method would be suitable for forming single bends, and what possible improvements have to be made to make high-quality bends.

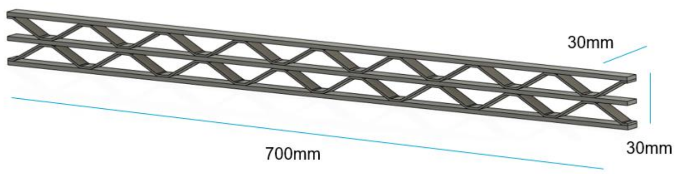


Figure 1 Conceptual level of the sandwich beam made using a corrugated core from laminate off-cuts

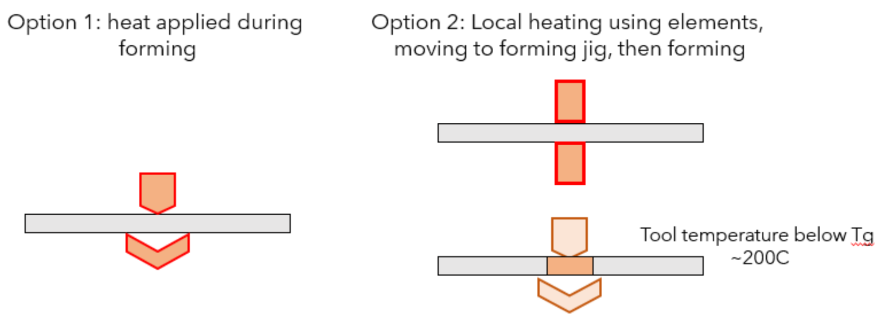


Figure 2 Two options for forming the bends in the laminate off-cuts

Method

To decide between the two methods, a simple forming experiment is proposed, where the forming time, spring-in angle and possible defects present are recorded. Three single bends are made using both methods, whilst using a varying forming pressure: 5, 25 and 50 bar. In this way, a suitable forming pressure can be determined simultaneously with the experiment.

For method 1, the procedure is as follows:

1. Heating of the tool in the oven until 350C
2. Removing of tools from the oven
3. Placement of the tools into pressure application device

4. Placement of blank under tool
5. Application of pressure to the blank, forming it to shape
6. Cooling of the tool and blank whilst maintaining pressure
7. Removal of blank and placement on cooling plate when temperature is below 200C
8. Further cooling to room temperature on cooling plate

For method 2, the procedure is as follows:

1. Heating of two blocks in the oven until 350C
2. Heating of two tools until 200C
3. Placement of the blocks on the blank
4. Maintaining contact of blocks with blank until blank reaches 350C
5. Removal of blocks and placement of blank under heated tool
6. Application of pressure to blank, forming it to shape
7. Bring to final forming pressure and hold for 3 minutes
8. Removal of blank from press and placement onto cooling plate
9. Further cooling to room temperature

Thermocouples will be used to monitor the temperature of the tools, and the blank. For the first method, thermocouples will be placed on the inside of the forming moulds and the top and bottom of the blank. For the second test, the same placement of the thermocouples for the blanks is used, and the temperature of the heating blocks is also monitored. This is shown in Figure 3.

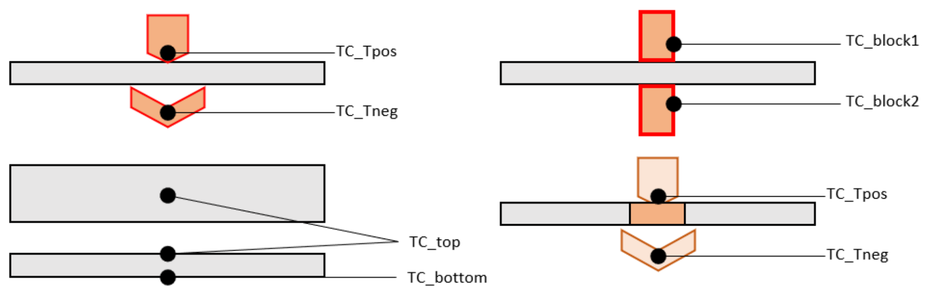


Figure 3 Thermocouple layout of method 1 (left) and method 2 (right)

For an initial assessment of the heating time for method 2, one of the heating blocks can be removed for a couple of seconds to gauge the temperature of the blank. Estimated time for heating is around 60-120 seconds depending on the thickness.

Material & processing parameters

The material used for the test is Toray Cetex 1100-PPS, with a plain weave carbon fabric reinforcement. The thickness will be around 1.5mm (8layers) , with a quasi-isotropic layup. The size of the blanks for the test will be 30x150x15mm. The processing parameters are summarised in table..

The pressure will be applied to an area of 100x30mm, which means that for 5, 25 and 50 bar a force of 1500, 7500 and 15000N (350, 1700 and 3350 lb.f) will have to be applied. On the press the ram force is shown in pounds.force, which will be leading for the reading of the applied loading.

Setup

The testing setup consists of multiple components, as listed in Table 1.

Table 1 Equipment used during the experiment

Component	Description	Picture
Matched moulds	Two mould halves positive and negative, made from steel. Are used to make a single bend of 90°.	
Heating blocks	Steel blocks that are used to heat the blank to the processing temperature for method 2	
Press	Press that is used to apply a controlled amount of pressure during the forming. Hydraulic pressure(PSI) or force (lb.f) can be read from the gauge next to the press.	 
Oven	Nabertherm Lv-5 oven, max 1300C. Used for heating the tooling to the processing temperature of the material. Internal dimensions 20x20x10cm. Heat resistant gloves are present nearby.	

Cart	Height adjustable cart that can be used for the transportation of the moulds to the composites lab. Possibly also to be used as a table for pressing close to the ovens if transport is not feasible.	

The attachment of the positive mould to the press is done through a threaded rod through the top of the press, and the bottom mould is held in place using two rectangular blocks. This is illustrated in Figure 5.

An overview of the setup layout on the composites lab table is shown in Figure 4, detailing the placement of the press, and two additional steel plates that are used for cooling the moulds and blanks after forming.

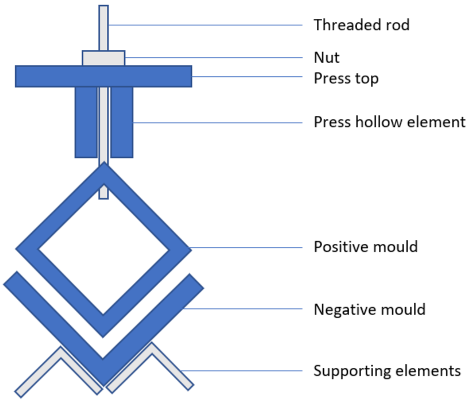


Figure 5 setup of the press with the positive and negative mould

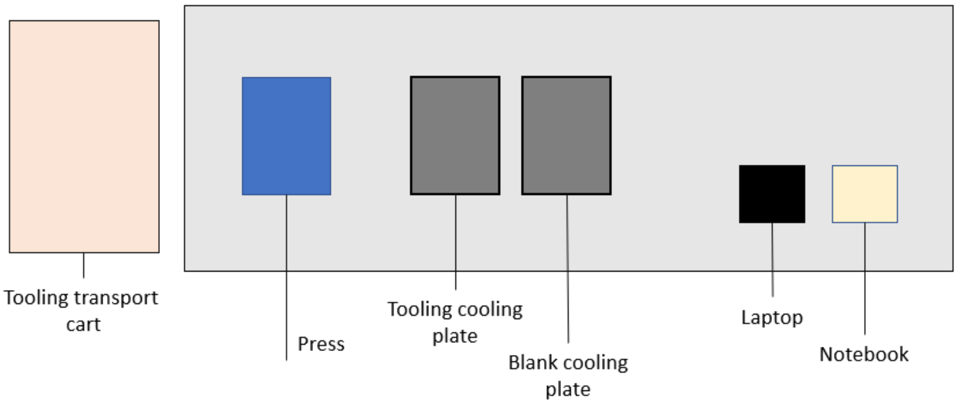


Figure 4 Table layout for the experiment in the composites lab

Results

The results are separated into two parts, one focused on the process itself, and one focused on the quality of the samples.

Process 1

The first process, using the heated tools to heat up the material and form at the same time, did not result in the ability to form a single bend. The tooling cooled too quickly from the transfer and assembly into the press, and reached well below the processing temperature of the material before the pressure could be applied. As a result, only a partial bend in the material could be made. The partial bend that could made is shown in ..

The partial bend sample did show an impression of the tooling, demonstrating that the material did have intimate contact with the tool. Throughout the forming process, cracking could be heard which indicated that the material was not at the processing temperature, and fibres were being broken due to elastic bending.

Process 2

The second process did allow for the material to reach the processing temperature, as the larger moulds had a higher thermal mass, and were able to retain their high temperature for a longer time. When the material was pressed between the two blocks, immediate melting of the polymer was visible on the outer surface of the material, as this spilled on the moulds. With increasing thickness of the material this immediate melting was still observed, although it might take more time to reach the centre of the material. During the transfer from heating moulds to forming moulds, the material remained in a molten state, which made the material very flexible and hard to properly align in the moulds. The pressure was applied quickly and during the closing of the moulds no cracking sounds were heard. When releasing the pressure the material released from the moulds easily and no excessive force was required.

The first sample tested was placed askew in the bottom mould, which caused the pressure to be applied incorrectly to the entire surface, shifting the material inside the tooling. The second sample was placed correctly inside the tooling, and showed a well aligned imprint of the tooling, indicating that this did not shift during the forming.. The third sample was of double thickness of the previous two samples and showed a similar imprint to the second sample, but a little wider due to the increased fit within the two moulds.

Discussion

A limitation of the comparison between the two processes is the rudimentary nature of the heating of the moulds, and the transfer time. If the transfer time could be shortened the results of both processes might be more relevant. Furthermore, if the moulds are heated in-place using a heating cartridge, the transfer time will be eliminated, and the outcome of the comparison can be changed. However, integrating a heating circuit with heat cartridges is resource intensive, and the point is to keep the processing a simple as possible. Therefore, the outcome of the test remains valid.

For the tooling, an obvious limitation is that the moulds do not align, resulting in uneven pressure application to the material. With this uneven pressure, uneven cooling rates can occur during the material, as the areas that are not connected to the tooling can cool more quickly than the ones in contact with the heated tooling. As such, the result of the spring-in angle cannot be used directly, but should be further analysed with moulds that do apply the pressure evenly.

There was also no way to keep tension on the material during the transfer from the heated tools to the pressing moulds, which could have caused deformation of the material. As the material was very flexible, it deformed during the transfer which could have introduced defects to the material before applying the pressure. Therefore, for further tests the integrity of the material should be ensure during the transfer.

Conclusions

For the processing method, it is clear that process 2 delivered satisfactory results, and was able to quickly heat up the material to the processing temperature, and resulted in bends that were formed through temperature, rather than elastic bending. Also, it showed that it could quickly adapt to a changing material thickness, by increasing the heating time, without any additional processing of the tooling.

For the tooling, steel proved to be a suitable material as the release agent remained on the material making release easy, the surface could make intimate contact with the material, and it did not deform under the large pressure during forming. Furthermore, it was able to withstand the high processing temperature, without losing its integrity.

For the material, single bends were formed but the quality of those was lacking. For future tests moulds should be used that are tailored to the material thickness, and the bend to be formed. Also, a mechanisms to keep tension on the material during the transfer should be used to retain its integrity, and apply deformation in a controlled manner.

K
Ideation round results

K.1. Ideation round 1

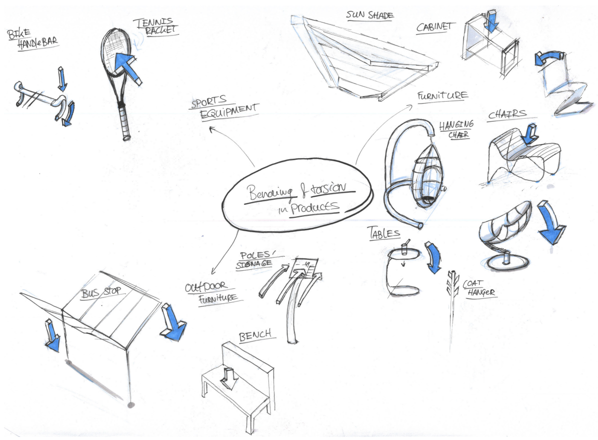


Figure K.1: Mindmap created around exploring product that feature bending and torsion loads

K.2. Ideation round 2

K.3. Ideation round 4

Figure K.2: Selected ideas generated during the three imagination rounds

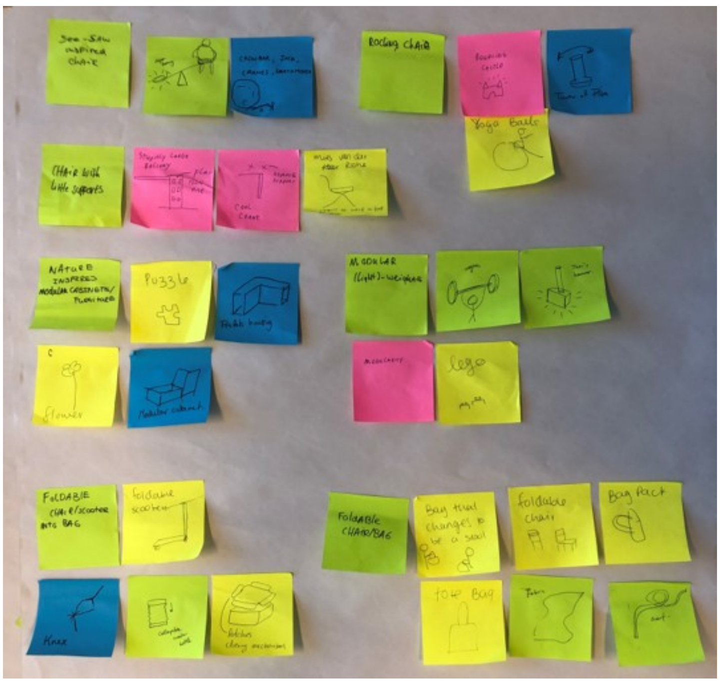


Figure K.3: Clustering of the generated ideas into new ideas

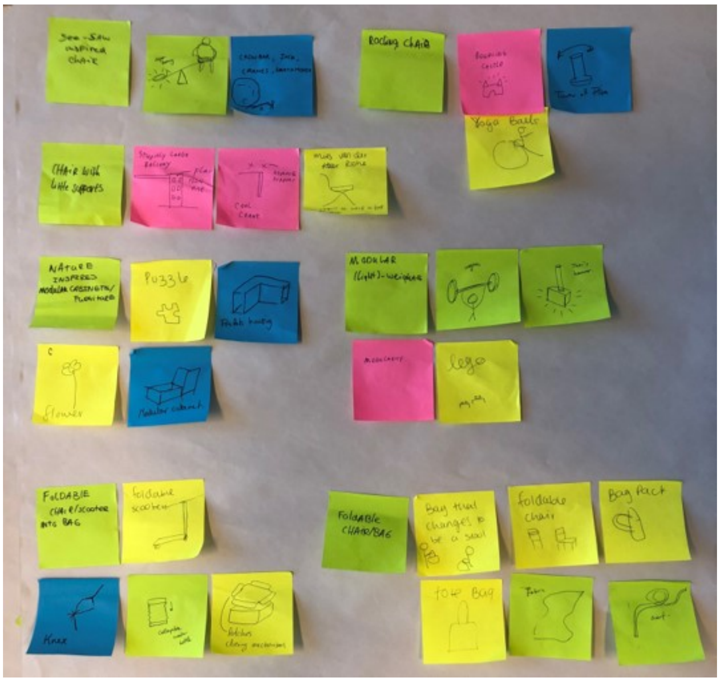


Figure K.4: Clustering of the generated ideas into new ideas

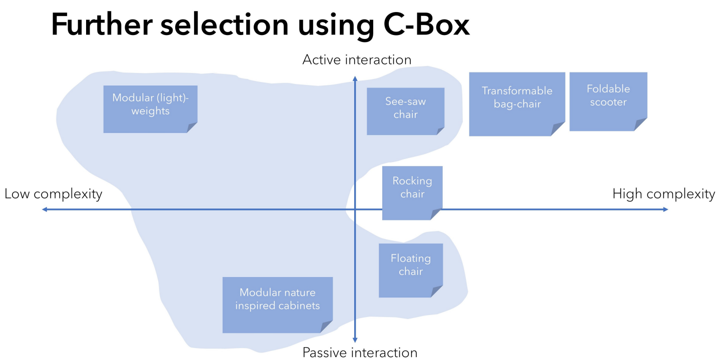


Figure K.5: Using a C-box to plot the ideas on an axis of complexity and interaction to narrow them down further

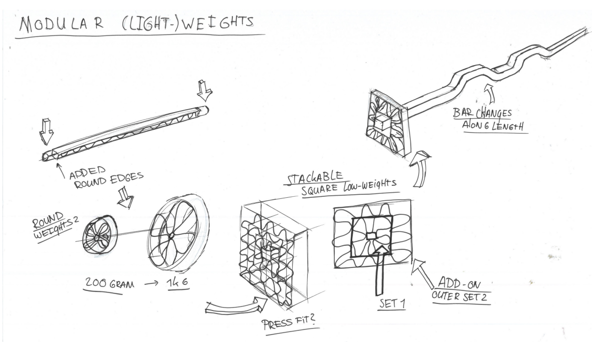


Figure K.6: Sketch of the modular (light-) weights idea

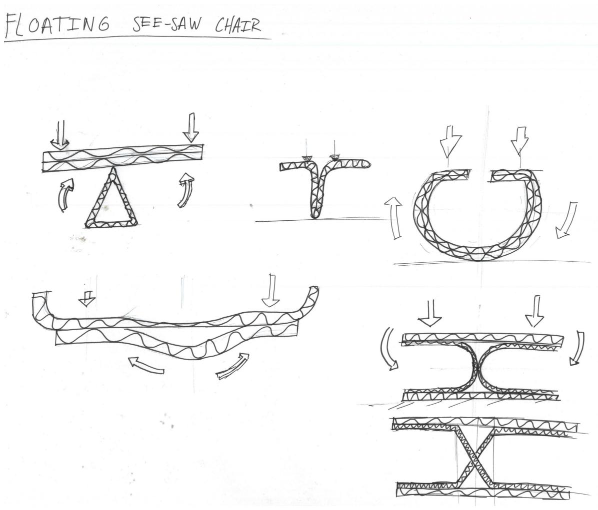


Figure K.7: Sketch of the floating see-saw chair idea

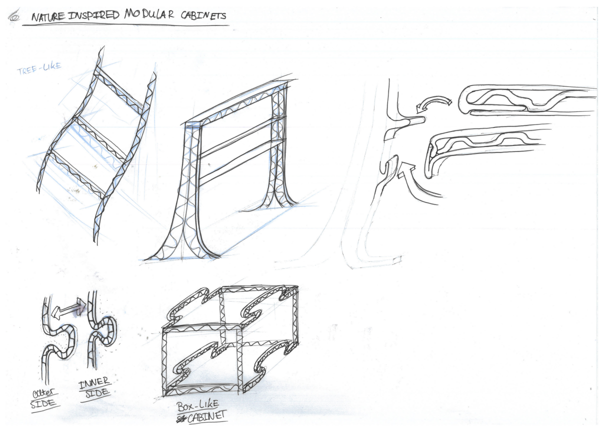


Figure K.8: Sketch of the nature inspired modular cabinets idea

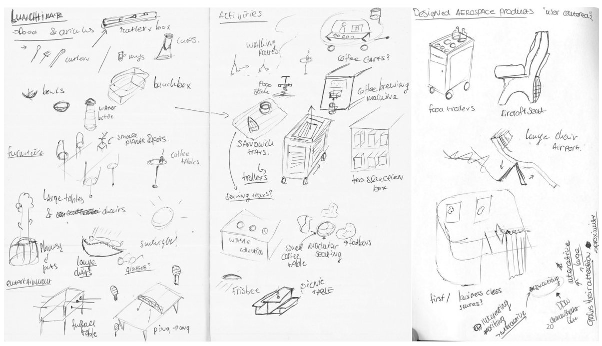


Figure K.9: Ideas generated around the common grounds of lunchtimen and designed aerospace products

L

Product idea selection details

Criteria	--	-	+	++
Allow for creative and novel material use	The product is purely driven by function and requires purely dedicated form	The product allows for little creative and novel use of the material	Some parts of the product allow for creative and novel use of the material	All of the product can be made using creative and novel use of the laminate off-cuts
Valuable and functional use of material	The product does not use any of the valuable properties of the material	The product uses one of the valuable properties of the material, with no result on its functionality	The product uses multiple of the values of the material, but with limited functionality of the product	The product uses a combination of the valuable properties of the material to enhance its performance
Familiar product	The product needs extensive explanation before the target audience grasps what the product is	The product needs some explanation before the target audience grasps what the product is	The product needs very little explanation to the target group to grasp what the product is	It is immediately apparent what the product is to the target group and other people as well
Interactive	It is not possible for the target group to interact with the product	Very limited interaction with the product is possible	The target group can interact with the product, but with some restrictions	The target group can interact with the product without any restriction
Engaging	The product does not engage the target group at all	A small part of the target group is engaged for interaction by the product	The product is engaging for most of the target group	The product is engaging for all viewers

Figure L.1: Specification of the different levels of the criteria used in the Harris profile for the product idea selection

Criteria	Windmill	Lamp	Bridge	Bird statue
Allow for creative and novel material use	(+) In the support of the windmill the material can be used in creative and novel way without affecting the function of the product	(+) In the supporting structure of the product the material can use used in creative ways without affecting the function	(+) The supporting and holding structure of the bridge can be made using creative ways	(++) The entire statue of the bird can be made using creative and novel ways of using the material, and can even positively influence its function
Valuable and functional use of material	(++) The mechanical properties of the material are utilised and can enhance the performance of the product as well.	(-) The lamp uses the conductive nature of the material, but using the laminate off-cuts has little value or functionality compared to any other conductive material.	(++) The bridge can use the mechanical, processing and aesthetic properties of the material to enhance its structural performance and influence its perception by the target group	(-) The aesthetic functionality of the material is utilised in the design of the bird, but using this specific material captures little of its value and functionality.
Familiar product	(++) a windmill is familiar for everyone in the target group as this is commonly seen in the public space	(-) The lamp is a novel object with a unique form and will require explanation to the target group. Its function and how the material is used also required explanation	(++) A bridge does not require explanation as this is common in the public space	(-) The relation between the bird and the material might required explanation for the target group, as the details of the material can be hard to see at a large distance. It might not be so apparent that this is made from aerospace material
Interactive	(--) No interaction with the windmill is possible	(-) limited interaction is possible through the reflections of the lamp on the water	(+) The target group can interact by touching and walking on the product, but can be limited to the non-structural elements of the bridge	(--) No interaction is possible with the statue
Engaging	(-) The rotation of the blades and the size of the product can make people turn around and look, but it does not draw them in for an interaction	(+) The lamp rotation and reflection can make people turn their heads and come over, and lure them for a limited interaction	(++) The bridge is inviting for the target group to try, and offers an interactive experience	(-) The bird statue can make people turn around, but offers limited interaction possibilities after that.

Figure L.2: Reasoning behind the ratings given to each criteria for the four ideas from the third ideation session

M
Second idea: bridge shape and form

The second idea was centred on having one central structural element, with cable elements supporting the deck of the bridge below. The initial exploration of the form of this bridge is shown in Figure M.1, with an exploration of the form of the structural elements as shown in Figure M.2. This idea uses a single solid structural member and suspension lines to create a streamlined and lightweight bridge. The structural member is the anchor of the bridge, demonstrating rigidity, motion and flow in a single shape. The streamlined effect is amplified by the suspension lines coming at the end, alluding to an increasing flow and velocity. The pedestrian/cyclist can experience the load bearing members up close, allowing them to experience the aesthetics of the material. This second bridge idea is not further investigated in the next sections as this type of bridge is more suitable for spanning longer lengths, as described in Section 6.4.1, leading to a overly complex design that is outside the scope of this project.

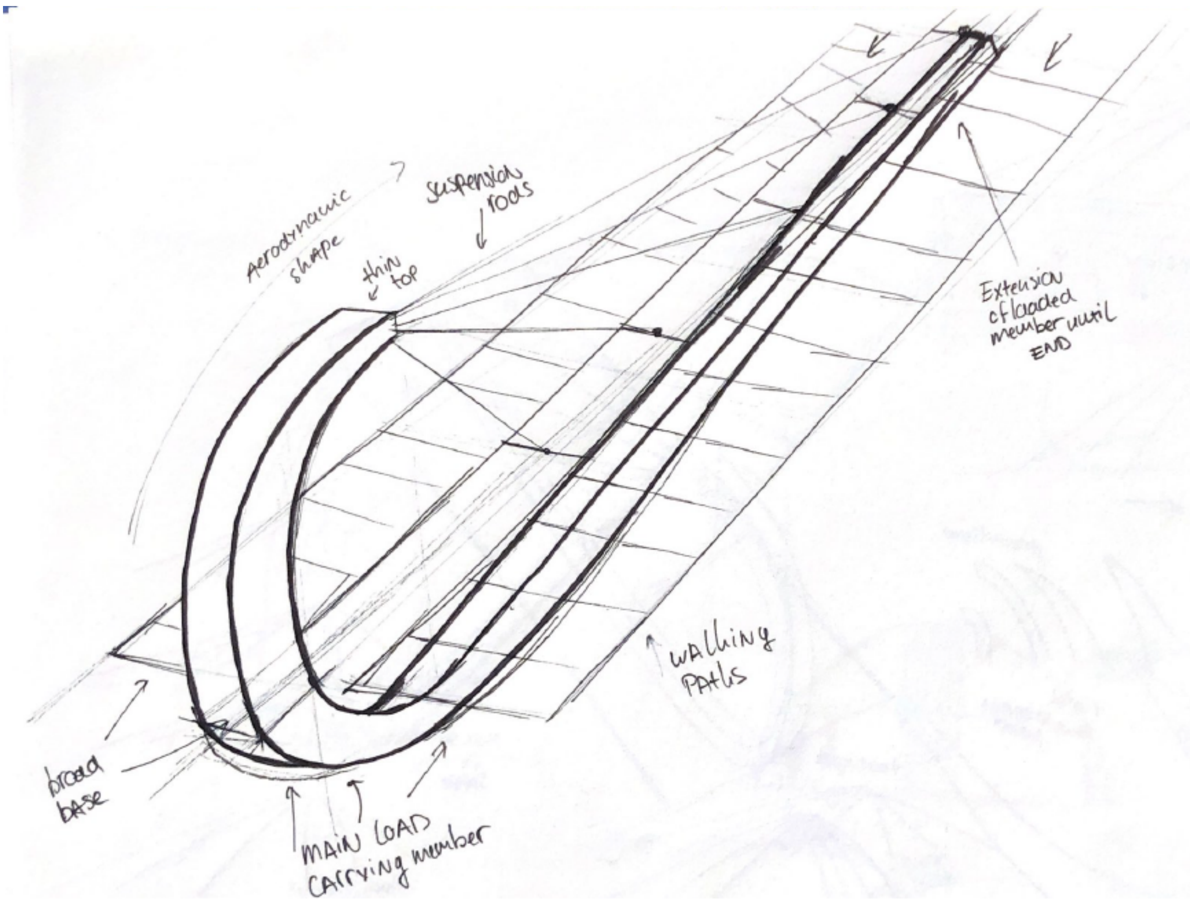


Figure M.1: Form and shape of the second bridge, featuring a single curved structural element in the middle with two walkways on either side

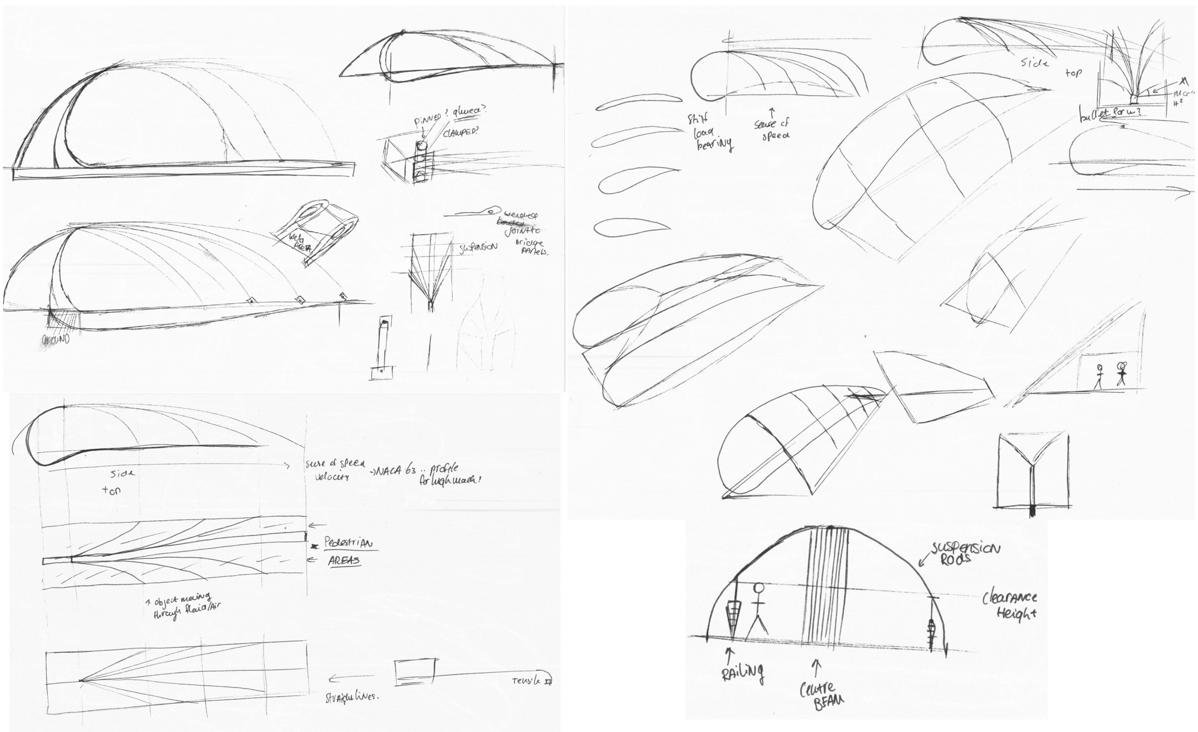


Figure M.2: Variations of the cross section and load carrying element of the second bridge idea

N
Laminate off-cut beam element calculations

In this appendix, the calculations used to calculate the stresses inside the load carrying beams of the bridge design that are made from the laminate off-cuts. In Figure N.1, the calculation procedure that is used for the defining the cross section of the laminate off-cut beams is further detailed. The relations used to calculate the deflection are taken from a mechanics of materials reference book [104]. The

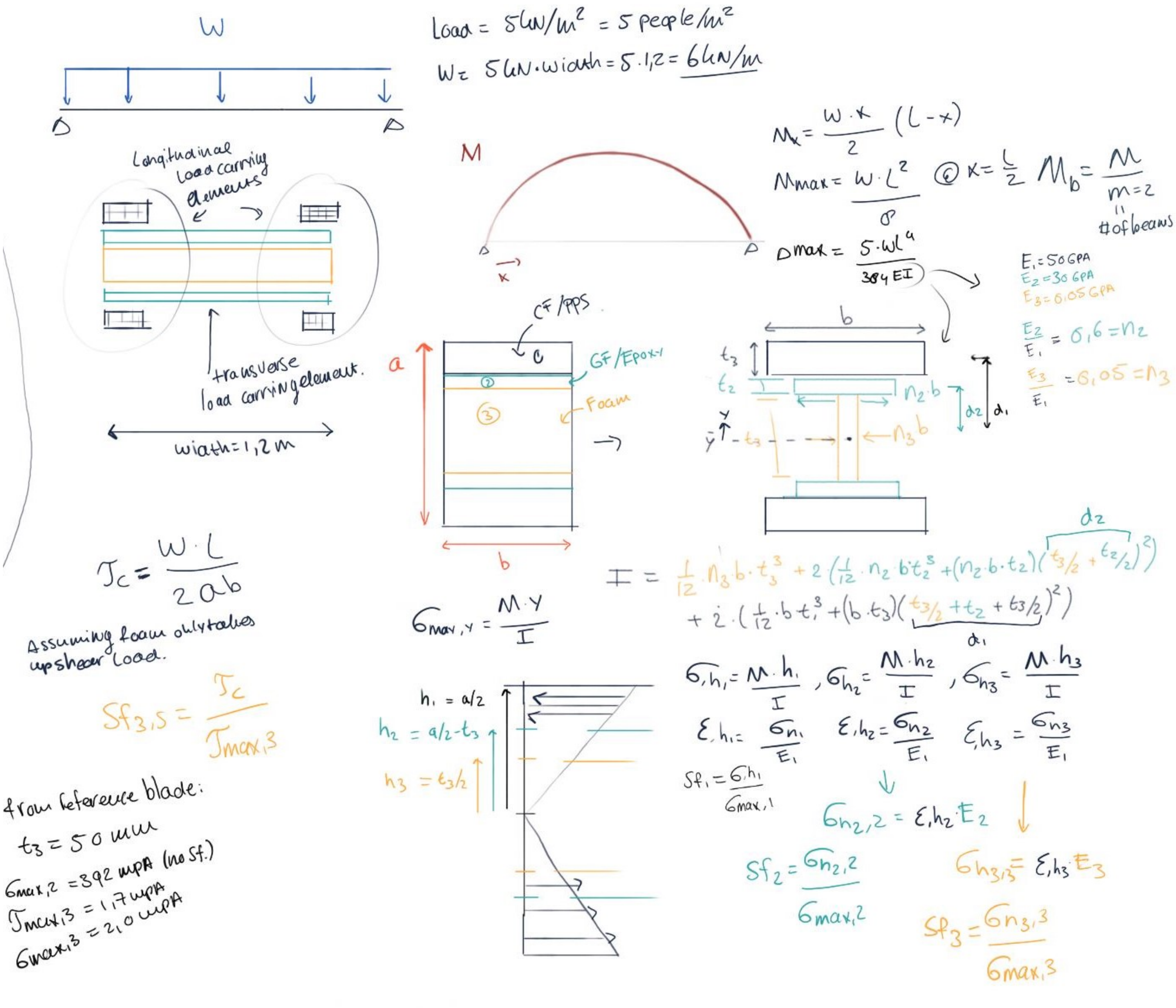


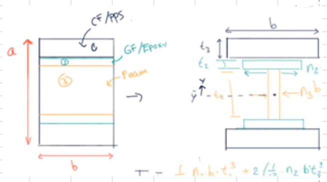
Figure N.1: Overview of how the cross section used for the beams made from the laminate off-cuts, and the relations used to determine the stress inside the material

calculations are performed in an excel sheet, as shown in Figure N.2 and Figure N.3. The material properties are taken from Table 2.8, Table 6.2, and the results are summarised in Table 6.3.

	A	B	C	D	E	F
1						
2						
3	**Geometric variables**					
4	L	2800	[mm]	length of the bridge ranging from 900-2800 for a single element, 1800-5600 for two elements together		
5	L_section	1400	[mm]	L @ reference blade = 43m		
6	a	=((B8+B11)*2)+B12	[mm]	height of the beam section		
7	b	150	[mm]	Width of the beam section (nominal width of the off-cuts is 37.5m)		
8	t1	30	[mm]	Thickness of the laminate off-cuts beam, thickness of the offcuts varies from 1-5mm		
9	a (nobeam)	=(B11)*2+B12	b(no beam)	=B15-2*B7		
10	**Geometric constants**					
11	t2	2.6	[mm]	Thickness of the glass fibre skins (from Joncas reference blade pg. 203, @ 17.0m length)		
12	t3	26	[mm]	Thickness of the core material (from Joncas reference blade pg. 203, @ 43m length)		
13	d1	=B12/2 +B11+B8/2	[mm]	Distance from the neutral axis to the centroid of the laminate off-cut section		
14	d2	=B12/2 + B11/2	[mm]	Distance from the neutral axis to the centroid of the glass fibre epoxy section		
15	W	1200	[mm]	Width of the bridge		
16	n2	=B23/B22	[-]	Ratio of the elastic modulus of the glass fibre/epoxy material over the laminate off-cut elastic modulus		
17	n3	=B24/B22	[-]	Ratio of the elastic modulus of the foam material over the laminate off-cut elastic modulus		
18						
19	I	=(1/12)*B17*B7*B12^3 + 2*((1/12)*B16*B7*B11^2 + (B16*B7*B11)*B14^2)+2*((1/12)*B7*B8^3 + (B7*B8)*B13^2)	[mm^4]	Area moment of inertia of the beam section		
20						
21	**Material properties**					
22	E1	50000	[Mpa]			
23	E2	30000	[Mpa]	Elastic modulus of the glass fibre/epoxy material (joncas pg. 199)		
24	E3	130	[Mpa]	Elastic modulus of the foam material (joncas pg. 199)		
25	sigma1_comp_max		193	[Mpa]	Compressive strength of the laminate off-cut material	
26	sigma2_comp_max		392	[Mpa]	Compressive strength of the GF/E material (joncas pg. 199)	
27	sigma3_comp_max		2	[Mpa]	From Airex reference material, density = 100kg/m^3	
28	sigma1_tens_max		254	[Mpa]	Tensile strength of the laminate off-cut material	
29	sigma2_tens_max		476	[Mpa]	Tensile strength of the GF/E material (joncas pg. 199)	
30	sigma3_tens_max		2.7	[Mpa]	From Airex reference material, density = 100kg/m^3	
31	tau_3_max		1.7	[Mpa]	From Airex reference material, density = 100kg/m^3	1.1 = airex c71.75
32						
33	**Loading & boundary c**					
34	Q	=6/1000/1000*1000	[N/mm^2]	Distributed load on the bridge		
35	q	=B15*B34	[N/mm]	Distributed line load		
36	M_x	=B35*B4*(B4-B37)/2	[Nmm]	Moment curve in terms of x		
37	x	900	[mm]	Distance x along the length of the beam		
38	m	2	[-]	number of load carrying beams		
39	M_max	=B35*(B4/2)*(B4-(B4/2))/2/B38	[Nmm]	Maximum moment per beam		
40						
41	**Stresses**					
42	Sigma_max_1		=B39*(B6/2)/B19	[Mpa]		
43	Sigma_max_2		=B39*(B6/2 - B8)*B16/B19	[Mpa]		
44	Sigma_max_3		=B39*(B12/2)*B17/B19	[Mpa]		
45	Tau_3		=B35*B4/(2*B6*B7)	[Mpa]		
46	tau3)sandwich		=B35*B4/(B9*D9)	[Mpa]		
47	**Deflection**					
48	delta	=5*B35*B4^4/(384*B22*B19)	[mm]	at L/2		
49	1% of span	=B4/100	[mm]			
50						
51	**Output**	x = L/2			x = L/4	
52			=B48			
53		sf1	=C25/C42			
54		sf2	=C26/C43			
55		sf3	=C27/C44			
56		sf3_shear	=C31/C45			
57		sf3_shear_sandwich	=C31/C46			

Figure N.2: Calculations used in excel to determine the stresses in the off-cut beams, with the relations highlighted for each cell

	A	B	C	D	E
1					
2					
3	**Geometric variables**				
4	L	2800	[mm]	length of the bridge ranging from 900-2800 for a single element, 1800-5600 for two elements together	
5	L_section	1400	[mm]	L @ reference blade = 43m	
6	a	91.2	[mm]	height of the beam section	
7	b	150	[mm]	Width of the beam section (nominal width of the off-cuts is 37.5m)	
8	t1	30	[mm]	Thickness of the laminate off-cuts beam, thickness of the offcuts varies from 1-5mm	
9	a (nobeam)	31.2	b(no beam)	900	
10	**Geometric constants**				
11	t2	2.6	[mm]	Thickness of the glass fibre skins (from Joncas reference blade pg. 203, @ 17.0m length)	
12	t3	26	[mm]	Thickness of the core material (from Joncas reference blade pg. 203, @ 43m length)	
13	d1	30.6	[mm]	Distance from the neutral axis to the centroid of the laminate off-cut section	
14	d2	14.3	[mm]	Distance from the neutral axis to the centroid of the glass fibre epoxy section	
15	W	1200	[mm]	Width of the bridge	
16	n2	0.6	[-]	Ratio of the elastic modulus of the glass fibre/epoxy material over the laminate off-cut elastic modulus	
17	n3	0.0026	[-]	Ratio of the elastic modulus of the foam material over the laminate off-cut elastic modulus	
18					
19	I	9198613.94	[mm^4]	Area moment of inertia of the beam section	
20					
21	**Material properties**				
22	E1	50000	[Mpa]		
23	E2	30000	[Mpa]	Elastic modulus of the glass fibre/epoxy material (joncas pg. 199)	
24	E3	130	[Mpa]	Elastic modulus of the foam material (joncas pg. 199)	
25	sigma1_comp_max		193	[Mpa]	Compressive strength of the laminate off-cut material
26	sigma2_comp_max		392	[Mpa]	Compressive strength of the GF/E material (joncas pg. 199)
27	sigma3_comp_max		2	[Mpa]	From Airex reference material, density = 100kg/m^3
28	sigma1_tens_max		254	[Mpa]	Tensile strength of the laminate off-cut material
29	sigma2_tens_max		476	[Mpa]	Tensile strength of the GF/E material (joncas pg. 199)
30	sigma3_tens_max		2.7	[Mpa]	From Airex reference material, density = 100kg/m^3
31	tau_3_max		1.7	[Mpa]	From Airex reference material, 1.1= airex c71.75
32					
33	**Loading & boundary conditions**				
34	Q	0.006	[N/mm^2]	Distributed load on the bridge	
35	q	7.2	[N/mm]	Distributed line load	
36	M_x	19152000	[Nmm]	Moment curve in terms of x	
37	x	900	[mm]	Distance x along the length of the beam	
38	m	2	[-]	number of load carrying beams	
39	M_max	3528000	[Nmm]	Maximum moment per beam	
40					
41	**Stresses**				
42	Sigma_max_1		17.4892436	[Mpa]	
43	Sigma_max_2		3.589897371	[Mpa]	
44	Sigma_max_3		0.012963518	[Mpa]	
45	Tau_3		0.736842105	[Mpa]	
46	tau3)sandwich		0.717948718	[Mpa]	
47	**Deflection**				
48	delta	12.5288441	[mm]	at L/2	
49	1% of span	28	[mm]		
50					
51	**Output**	x = L/2			x = L/4
52			12.5288441		
53		sf1	11.03535432		
54		sf2	109.1953222		
55		sf3	154.2791051		
56		sf3_shear	2.307142857		
57		sf3_shear_sandwich	2.367857143		



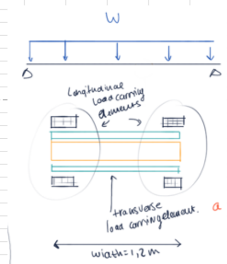


Figure N.3: Calculations used in excel to determine the stresses in the off-cut beams, with the values highlighted for each cell

O
Final bridge concept user evaluation

In this appendix chapter the questions posed to the participants of the test are presented, as well as informed consent form that each participant completed. These consent forms are available upon request.

O.0.1. Overall design evaluation

1. Sheet of thermoplastic composite material
2. One laminate off-cut
3. Picture of final concept design
4. Thermoplastic composite model of the railing
5. Thermoplastic composite model of the coiling
6. Thermoplastic composite model of the single bend
7. Thermoplastic model of the twist

O.0.2. Test questions

1. From first glance, what do you see as the value of the material?
2. How would you judge the functionality of the material?
3. What is your first impression of the shaping possibilities of the material?
4. What do you think stands out?
5. What would you make out of the material, taking the value and the shaping possibilities in mind?
6. Did the demonstrator help you in finding new applications of the material?
7. If this was a railing on a bridge, would you have any resistance to grabbing it?
   (a) If not, why?
   (b) If yes, why?

Participant ID:

Evaluation of bridge design

This research is conducted as part of the MSc study Industrial Design Engineering at TU Delft.

Students: Sam Lonis
Contact person: Sam Lonis, samlonis@gmail.com , +31631324466

Informed consent participant

I participate in this research voluntarily.

I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research.

I am aware that this research consists of the following activities:

1. Observe overall CAD design of the bridge
2. Observe prototype reshaped railing elements
3. Observe prototype structural beam element
4. Observe prototype railing handle
5. Be interviewed about the experience of these bridge components

I am aware that data will be collected during the research, such as notes, photos, video and/or audio recordings. I give permission for collecting this data and for making photos, audio and/or video recordings during the research. Data will be processed and analysed anonymously (without your name or other identifiable information). The data will only be accessible to the research team and their TU Delft supervisors.

The photos, video and/or audio recordings will be used to support analysis of the collected data. The video recordings and photos can also be used to illustrate research findings in publications and presentations about the project.

I give permission for using photos and/or video recordings of my participation:
(select what applies for you)

- ☐ in which I am recognisable in publications and presentations about the project.
- ☐ in which I am not recognisable in publications and presentations about the project.
- ☐ for data analysis only and not for publications and presentations about the project.

I give permission to store the data for a maximum of 5 years after completion of this research and using it for educational and research purposes.

I acknowledge that no financial compensation will be provided for my participation in this research.

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

The researchers take the COVID-19 measures into account. I confirm to respect the COVID-19 measures taken and will follow instruction about these provided by the researchers.

I will receive a copy of this consent form.

_______________________ _______________________

Last name First name

___ / ___ / 2023

____

Date (dd/mm/yyyy) Signature

P
IDE graduation project brief

This chapter of the appendix contains the approved graduation project brief from the faculty of Industrial Design Engineering.

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Lonis 6267

initials: S.V. given name: Sam

student number: 4313712

street & no.:

zipcode & city:

country:

phone:

email:

Your master programme (only select the options that apply to you):

IDE master(s): IPD (selected) / DfI / SPD

2nd non-IDE master: Aerospace Engineering

individual programme: - - (give date of approval)

honours programme: Honours Programme Master

specialisation / annotation: Medisign / Tech. in Sustainable Design / Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Ruud Balkenende — dept. / section: SDE

** mentor: Clemens Dransfeld — dept. / section: AE / AMT

2nd mentor:

organisation:

city: country:

comments (optional): Clemens Dransfeld is the chairholder of the Aerospace Manufacturing Technologies at the Aerospace Engineering faculty of the Delft University of Technology, and will act as a mentor from the Aerospace Engineering faculty

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

Digitally signed by Ruud Balkenende - IO
Date: 2023.03.09 08:24:39 +01'00'

chair Ruud Balkenende date 09 - 03 - 2023 signature

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 30 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 30 EC

★ YES all 1st year master courses passed

NO missing 1st year master courses are:

List of electives obtained before the third semester without approval of the BoE

Variant for Engineers

Robin den Braber

Digitaal ondertekend door Robin den Braber
Datum: 2023.03.09 08:29:52 +01'00'

name Robin den Braber date 09 - 03 - 2023 signature

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ★ APPROVED NOT APPROVED

Procedure: ★ APPROVED NOT APPROVED

- late submission projectbrief has been discussed with the chair

comments

name Monique von Morgen date 06 - 03 - 2023 signature

Re-use of thermoplastic composite production waste

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 05 - 09 - 2022 31 - 07 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The total aviation sector is responsible for roughly 2.4% of global CO2 emissions, and the aviation industry is put under pressure to reduce the CO2 emissions as much as possible. Aircraft manufacturers are using composites in aircraft structures to lower the weight, leading to less fuel use and lower emissions during use [1][2]. This increased use of composites is apparent in newer generation aircraft, such as the airbus A350 and the Boeing 787, of which the aircraft structure consist of more than 50% by weight out of composites [3].

The use of thermoplastic matrix composites in aircraft structures is increasing due to the high processing rates, favourable storage conditions, improved chemical resistance and toughness and recycling opportunities of thermoplastic materials compared to thermoset materials [4].
Smaller thermoplastic composite components are produced using a thermoforming process which entails heating the material until softening and then using pressure for shaping and consolidation. For larger components the layup is done by hand or using robots through automation and an autoclave or press is used for consolidation [5].
The excess material during production is commonly referred to as production waste. Depending on the type and stage of processing, 5-50% of the material can be considered waste, where the majority consists of multiple plies rather than single plies [6]. In some cases this material has defects such as fibre wrinkling, misalignment of the fibres and can be contaminated with coatings, films and other types of contaminants. An overview of the different types of thermoplastic composite production waste during part manufacturing are shown in Figure 1.

Currently, the value of the thermoplastic composite production waste from the aerospace industry is not fully captured. Most of this is material discarded by the material and part manufacturers and only a small portion is recycled [7][8]. As the supply of production waste material is not homogeneous, studies in the past have attempted to transform the heterogeneous supply of waste material into a homogeneous material through size reduction and mixing of the waste materials. In this process the fibres are cut into smaller dimensions, sacrificing mechanical properties for improved processing possibilities, resulting in lower grade applications such non-structural hatches/panels and hinges [6][9]. Furthermore, the damage from size reduction cannot be undone, limiting the scope of applications after the end-of-life of these components further.
However, re-use without reducing the fibre length is possible through shaping, as the processing of thermoplastic composite materials is purely physical and reversible [10].

Main opportunities include the access to high performance materials for a fraction of the cost, and the shaping and joining options. Having access to high-performance materials for low cost can be beneficial for applications where high-performance materials are valued (allowing for weight savings or higher performance), but have been omitted due to their high cost [11]. Through shaping and joining, larger structures can be made out of smaller pieces of waste material, which can be tailored to a suit a specific function.

Possible limitations include the variety in the waste material, the instable supply and the processing conditions. Applications and structures designed from a single waste type are only limited to that specific definition of that waste type due to a large variety in matrix type, fibre type, layup, geometry and contaminants. There is also very limited influence on the properties and quantity of the supply of the production waste. Also, aerospace grade matrix materials (LMPAEK, PEKK, PEEK) require very high processing temperatures, which require dedicated tooling for processing.

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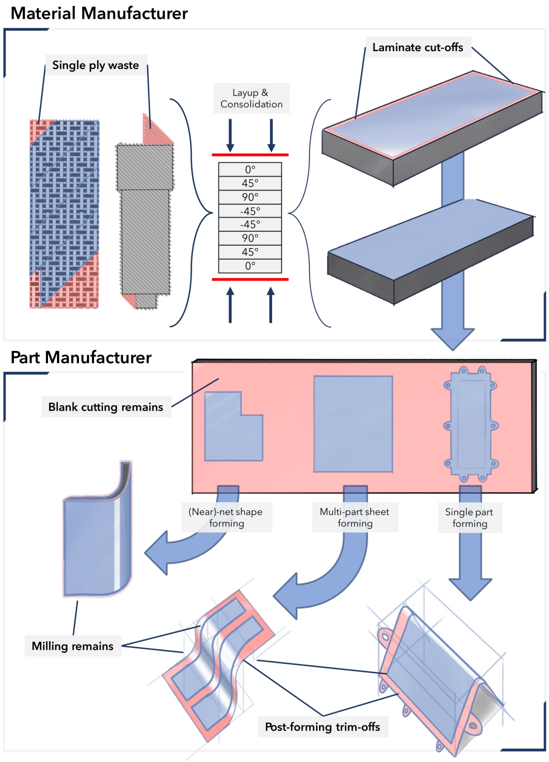


image / figure 1: Overview of the different types of production waste from a thermoforming process

image / figure 2:

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

One issue to address within this project is to find an application (on a part/structure level) that values the performance of the material, and where the production waste material can offer improved performance.

Another aspect is to design a competitive structure using this defined production waste material, whilst maintaining the material integrity and meeting the requirements of the part/structure.
Furthermore, the effect of the degree of shaping on the material integrity of the material is largely undefined and not easily estimated, and will have to be assessed and included into the design.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

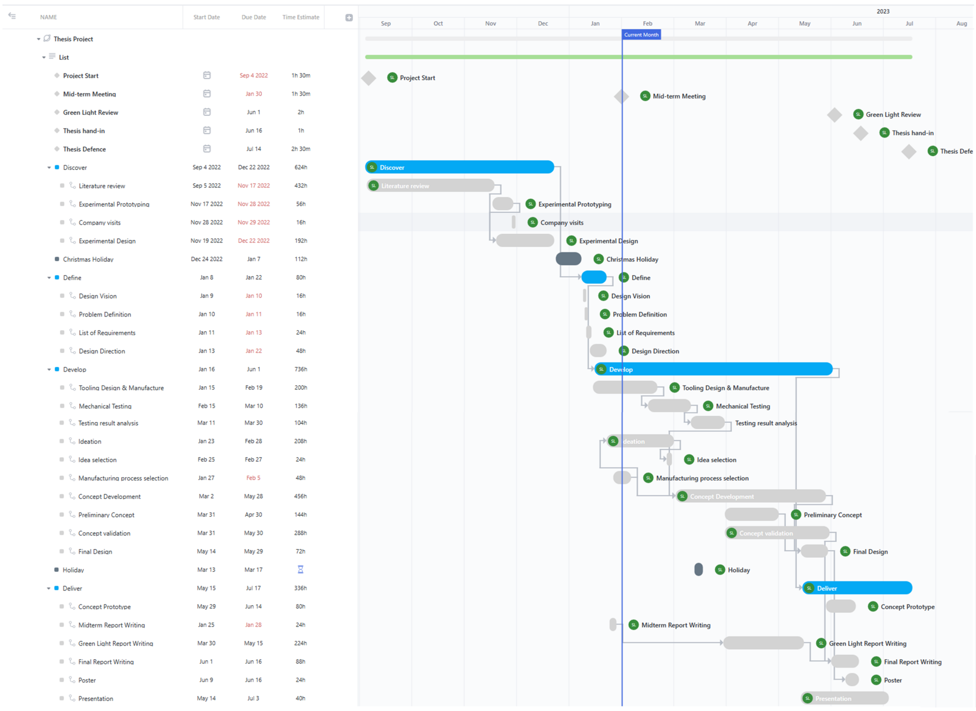
Develop guidelines for engineers and designers that allows them to find new applications for thermoplastic composite waste whilst retaining the value of the material and demonstrate this by using thermoplastic composite waste from the aerospace industry as input for the design of a new application within the automotive industry.

During this project a part of an automotive structure is designed using thermoplastic composite production waste as a starting point. The application is to be a structural component or any other component that values high-performance materials. Its

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 5 - 9 - 2022 | 31 - 7 - 2023 end date



This graduation project is combined with the thesis project of the Aerospace Engineering MSc programme, and the total work load is expressed as 63 ECTS, which comes to 44 weeks of work. The greenlight meeting is planned 4 weeks before the thesis defence. Weekly meetings are planned with the graduation committee, alternating from AE, IDE and AE & IDE combined. At least 2 working days before each meeting an agenda and presentation is sent in preparation.

The project follows the four main steps: Discover, Define, Develop and Deliver and each of the relevant phases during the project are detailed in the Gantt chart.

For the concept design, the structural and geometric requirements will be based on data from the industry or literature, to make the design as realistic as possible. A further detailing of the effect of the processing parameters on the mechanical properties of the formed structures will be performed during the conceptual design, specifying the processing boundaries. These will be formulated into guidelines and used to guide the geometry of the concept. The conceptual design is visualised through sketching and CAD, supported with small scale prototypes. A full scale proof of concept, possibly to be used for structural validation, is seen as an essential part of the deliverables.

Important dates:

Project start:	05-09-2022	Green light review:	03-07-2023
Project Kick-off:	26-09-2022	Thesis hand-in:	17-07-2023
Mid-term Meeting:	30-01-2023	Thesis presentation:	31-07-2023

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

I set up this project as I wanted to explore a more holistic approach to engineering and apply this in a relatively new field of study. I like the challenge of understanding structures and their behaviour, and composite structures open both a world of freedom in design, but also a challenge in structural analysis. I want to explore throughout this project how to use composite materials in a design process, exploring the limits of design whilst keeping the possibility of analysing and optimising a structure. I aim to design meaningful structures that are well thought out and make use of the performance of the material.

I started with the Aerospace Engineering MSc programme with a specialisation in structural analysis to learn more about the structural analysis of composite structures, and only discovered that it is more complex than I previously thought. I have learned the basic skills of how to analyse a structure and how to optimise this for a given load condition, but only for very simple applications. Within this project I hope to explore further how to apply this to structures.

While I was working at the Dreamteam Dare Aerospace Rocket Engineering and at Airborne Composites Automation I became very interested in process engineering, especially for composite materials. I learned how to design tooling specifically for automated composite production, how to build and design prototype processing equipment and the importance of guaranteeing certification/reliability during manufacturing. These skills I hope to apply during the design of the tooling and equipment, the sample manufacturing for the experimental testing and the manufacturing of the full-scale prototype.

After experiencing the minor sport innovation I always wanted to explore industrial design further as I liked the design approach and that the projects were smaller and more aimed towards the user. During the Integrated Product Design MSc programme I learned more about practical skills how to approach the concept and embodiment of a design, and also how to integrate the user in the design. Throughout this project there is not a specific defined user, but the customer in this case can be found in an automotive part manufacturer, and I aim to apply the skills I learned to also take their needs into account in the design.

Furthermore I became more familiar with the concept of the circular economy, and the role that composites play in this. I aim to integrate a part of this in the design by ensuring that the integrity of the material is retained, allowing for a next lifecycle to make use of the high mechanical properties that composite materials offer.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

I am aware that the submission of this form comes late in the project, this was due to a misunderstanding from my side. I tried to fill out the form with the knowledge that I have now, and am looking forward to the response from the board of examiners.

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