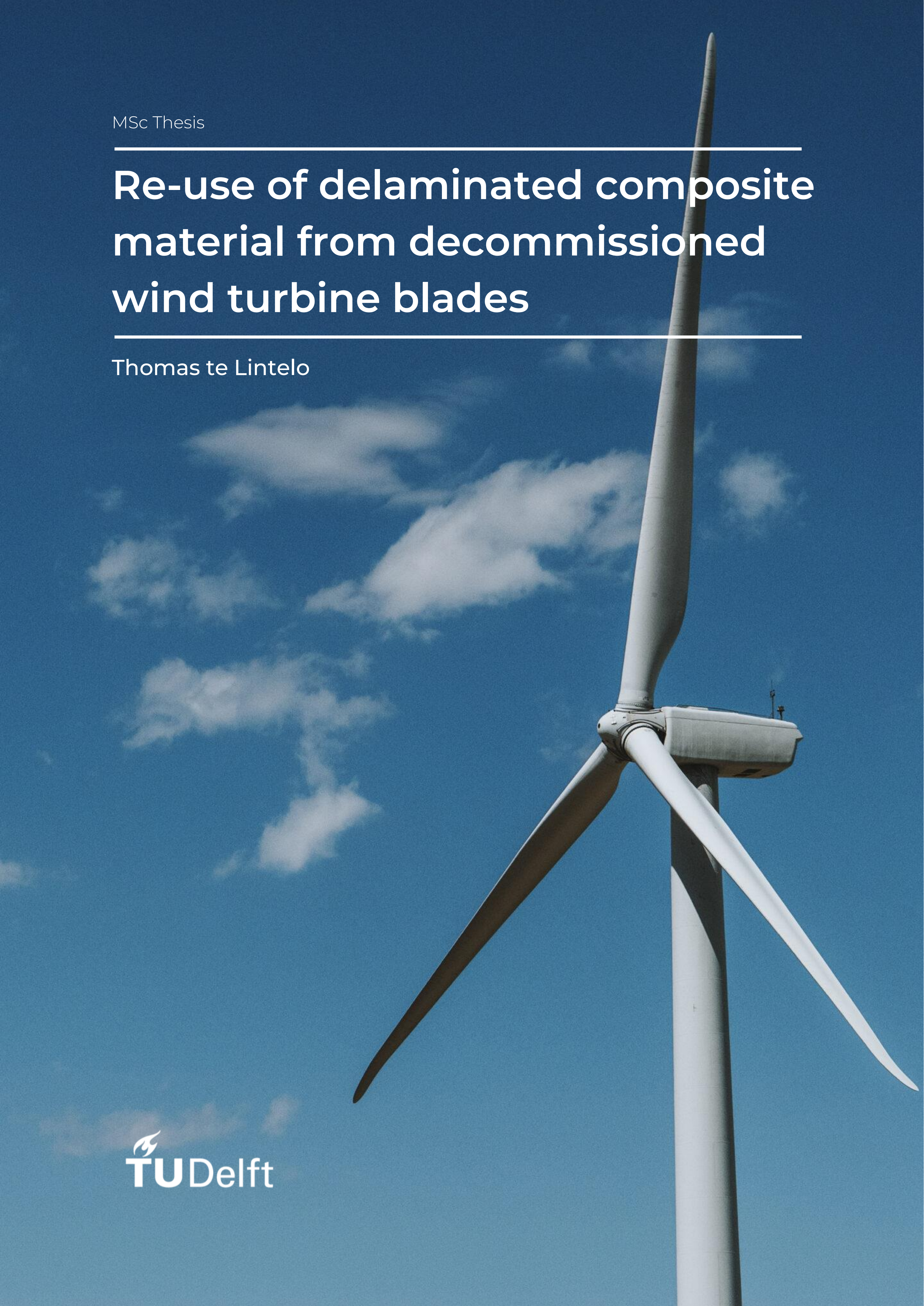
MSc Thesis

Re-use of delaminated composite material from decommissioned wind turbine blades

Thomas te Lintelo



TU Delft

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Re-use of delaminated composite material from decommissioned wind turbine blades

By

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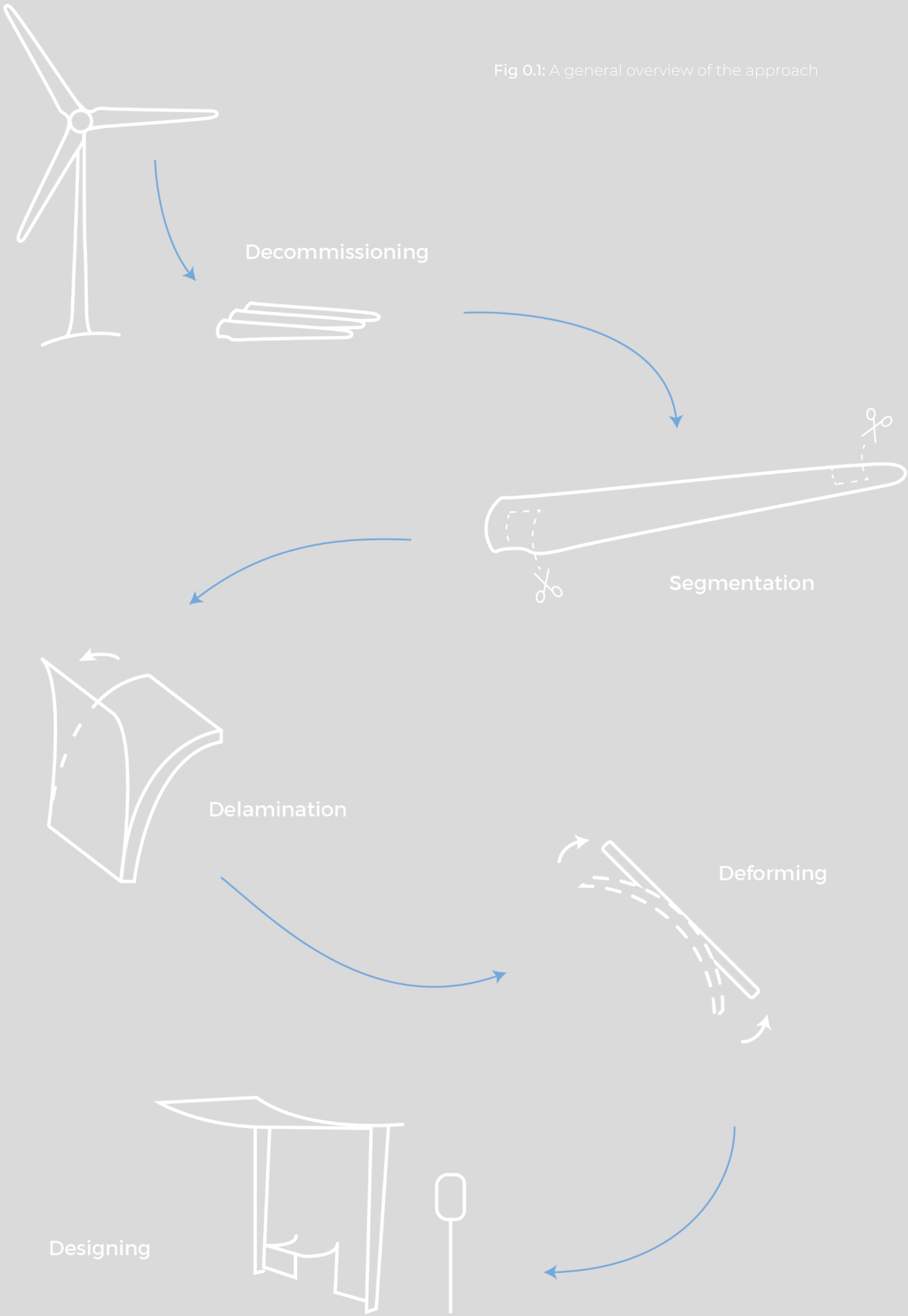
Fig 0.1: A general overview of the approach



Summary

More and more wind turbines are erecting in the landscape, stemming from the need for sustainable energy. However, less attention is paid to the secondary effects of these wind turbines, more specifically, the wind turbine blades. Wind turbine blades are made of composite material, a material that provides many advantageous properties for the desired functionality. Nevertheless, the material is difficult to reuse or recycle after the lifespan of the wind turbine blade. This challenge is expected to result in thousands of tons of decommissioned blades entering the market in the coming years which, due to the absence of good alternatives, are most likely to be disposed of in an unsustainable manner.

This project focuses on how composite material from decommissioned wind turbine blades can be reused in order to retain the value embedded in the material. It explores how delamination can potentially add to design freedom of the material for it to be used in a scalable way and match the large influx of the material. Focus is put on the curved elements of the blade: the inboard and outboard sections. Aside from producing scientific knowledge on the topic, the aim is to exhibit the findings through means of a demonstrator of a potential reuse application.

In chapter one, the thesis starts with research into background information, identifying the knowledge gap, setting the scope and conceiving the mission and research questions for the project. Then, in chapter two, a better understanding of a wind turbine blade is formed based on a reference blade. After this the geometry of the blade parts in focus, together with the material composition is researched. Chapter three dives into the possibilities of retrieving elements out of wind turbine blades and looks at the characteristics of these elements.

In chapter four the delamination of the sandwich structured wind turbine material is explored. It is investigated how this can be done and what potentially influences this process. Then, in chapter five the material characteristics of the retrieved and delaminated elements are analysed. This showed that the material can be elastically deformed, opening up the floor for a broader range of reuse applications.

The most suitable reuse application is then methodically determined in chapter 6. Based on, amongst other things, the material qualities and the vision, the choice fell on a bus shelter. A concept of this is then proposed and concretised in the form of a demonstrator. It exhibits the possibilities of the material and embodies the approach for facilitating reuse of decommissioned wind turbine blades on large scale as presented in the project.

In the end, the report concludes with an evaluation of the design and the process in the form of a discussion, a summary of the findings and multiple recommendations to improve future sustainability with respect to wind turbine blade material.

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Acknowledgements

Coming to Delft as an 18 year old and now leaving as a 23 year old I have been able to develop myself greatly, both on a personal and professional level, through three years of Bachelors, a full time year as part of Eco-Runner Team Delft, two years of Masters and several activities on the side. But above all, I have had a wonderful time and I am grateful for all the things I got to experience.

Delivering this thesis marks the end of these six years at the Delft University of Technology and I am pleased that I was able to initiate this project and receive help of many people from the faculty. This made me thoroughly enjoy my graduation project and kept me motivated to come to a result until the end as I believe the outcome can really contribute to the development of a more circular economy for composite material and ultimately lead to a more sustainable world to live in.

However, I would not have been able to finalise this project without the help and support from a number of different people and companies, which I would like to thank them for.

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Nomenclature

FRP = Fibre reinforced polymer
GFRP = Glass fibre reinforced polymer
UD = Uni-directional

Fig 1.1: Wind turbine in the Netherlands (*Tacconi, 2021*)

1. An introduction to the problem and its context

Chapter 1 will dive deeper into the exact problem to be tackled. First the context of the current situation is outlined, and it is then elaborated why this situation is undesirable. Thereafter the concept of the circular economy is introduced as a possible solution, together with its shortcomings. From this follows the exact underlying problem after which a knowledge gap to possibly solve it is identified. Research questions are then derived and the method for answering them is discussed.

1.1 A high demand for renewable energy

Organisms require energy to do work. By learning how to change energy from one form to another and then use it to do work, humans have been able to build the civilisation that we have today (*U.S. Energy Information Administration, 2022b)*. We use it to turn on lights and faucets, to drive bikes or cars, to cook food, or to manufacture all the things we use. It fuels our whole world. However, globally this energy is sourced primarily from non-renewable energy sources (*Ritchie et al., 2022*), meaning that the amounts are limited. Moreover, the main non-renewable energy sources are fossil fuels such as coal, natural gas and oil (*Ritchie et al., 2022*). Burning these fossil fuels in order to utilise the energy releases carbon dioxide (CO_2) into the atmosphere, a number which has sextupled since 1950 (*Ritchie et al., 2020*).

A surplus of these CO_2 emissions is the primary driver for the rise in the earth's average temperature. This has adverse consequences to our nature and brings threats to our society and businesses. On top of that, the air pollutants coming from the burning of fossil fuels are directly noxious to humans as well, resulting in estimates between 3.6 million (*Lelieveld et al., 2019*) to 8.7 million (*Vohra et al., 2021*) premature deaths a year. For these reasons it is evident that we need to decarbonise our energy systems, shift away from fossil-based systems of energy production and consumption, and move towards clean and renewable forms of energy: green energy.

Renewable energy comes from renewable sources like wind, the sun or the water cycle and does not cause emission when being generated. Progress is being made in this regard and the share of renewable energy has been increasing since the 1960s (*IEA, 2022b*; *Ritchie et al., 2022*). Moreover, the world is planning to expand the renewable capacity in the next 5 years with as much as it did in the past 20 years (*IEA, 2022b*). Wind energy is such a promising and therefore rapidly growing renewable energy source: its current global installed generation capacity is more than 55 times larger than it was two decades ago (*Irena, n.d.*; *Ritchie et al., 2022; IEA, 2022c*). The machinery making this possible, wind turbines, convert the kinetic energy of the wind, a renewable energy source, into electrical energy without emissions while doing so. Therefore, to meet future renewable energy demands, large wind turbine projects are being executed and the generation capacity is set to almost double over the 2022-2027 period (IEA, 2022a). Also, wind turbines themselves are ever getting bigger: in 1980 the average capacity of a wind turbine was 50kW with a rotor diameter of 15m (*Tarfaoui et al., 2017*), currently companies such as Vestas and Siemens Gamesa are manufacturing wind turbines capable of producing up to 15mW with a rotor diameter of 236m (*Myers, 2022; Lewis, 2023*).

1.2 Secondary effects of renewable energy production

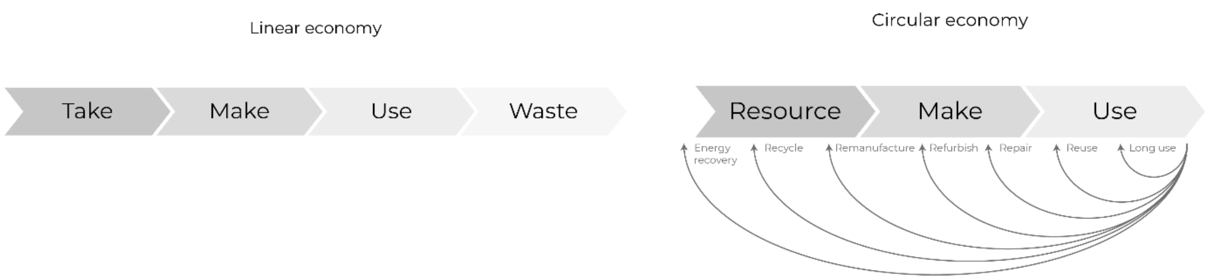
However, less attention is paid to possible secondary effects of this renewable energy production. Although the majority of a wind turbine is recyclable, there is much uncertainty on how to properly and safely handle the rotor blades at the end of their lifetime (*Andersen et al., 2014*). The use of composite materials in the wind turbine blades provide many advantageous properties for the desired functionality. Nevertheless, the challenge with composites at the end of wind turbine blade's life is expected to result in thousands of tons of decommissioned blades entering the market in the coming years. The exact numbers vary, Liu and Barlow (2017) foresaw that in 2022, in Europe, the total mass of decommissioned wind turbine blades was more than 50 ktons, Albers et al., in 2009, forecasted 50 ktons in 2020 and the ETIPWind Executive Committee predicts that in 2025 the blade waste will be 66 ktons. The latter said in 2019 that 15,000 wind turbine blades would be decommissioned in the next five years. In 2021 alone, 29,234 wind turbines were installed worldwide (*Global Wind Energy Council, 2022*), meaning that with an average life time of 20 years (*Yang et al., 2012*) and each of the three blades weighing a safely taken average of 10 tons (*Red, 2008/2022; Liu & Barlow, 2015*), in 2041 the amount of wind turbine blade waste is almost 1 Mt. Liu and Barlow (2017) even estimate a global annual waste of 2 Mt in 2050 and a cumulative waste of 43.4 Mt as the most probable number (*Beauson et al., 2021*). These are huge numbers. Due to the absence of good alternatives (see appendix B), these blades are most likely to be disposed of through landfilling or incineration, both of which are undesirable from many perspectives (*Mattiello et al., 2013*). Therefore, finding a solution for the decommissioned wind turbine blades is a pressing issue.

1.3 The circular economy

Landfill or incineration of wind turbine blade waste are an example of a linear ‘take-make-use-waste’ economy. In order to not run out of the finite resources the earth has to offer, the concept of a circular economy eliminates waste and sees it as non-existent. Instead, the resources are looped back into the economy at the end of their life, making it circular (*Ellen MacArthur Foundation, n.d.-c*). This way resources are used rather than used up and both the finite tap currently pouring newly extracted materials into the economy and the tap sending a stream of waste into landfills and incinerators can be closed. This is advantageous from both an economic and environmental perspective (*Balkenende et al., 2018*).

Within the circular economy, it is important and most beneficial to circulate the products and materials at their highest value, in the so-called ‘inner loops’. This means keeping the product or material as identical to its original state, or in a state as close as possible to its original function for as long as possible in order to retain more of the valuable labour, energy and material embedded in the product (*Den Hollander, 2018; Ellen MacArthur Foundation, n.d.-a*). Bakker et al. (2018) calls the extent to which a product remains identical the ‘product integrity’ and for the earlier mentioned benefit it is preferred to preserve this. When this is no longer possible, for the same reasons, it is best to preserve the material as close to their original state, which is described as the ‘material integrity’.

Fig. 1.2: Visualising the linear vs circular economy.



1.4 The problem with blade material and the circular economy

However, the exact applicability of the circular economy frameworks to the material out of which wind turbine blades are made: fibre-reinforced polymer composites, was largely unknown. Yet, Joustra et al. (2021b) developed a framework with strategies and design aspects to support the preservation of the product and material integrity of composite material for a circular economy (figure 1.3). It was concluded that the circular framework could largely be applied to current wind turbine blades with regard to the preservation of the product, but that this is different with regards to the material. A more thorough explanation of this 5-step framework together with the current status quo of wind turbine blades can be found in appendix B.

Design Aim	*Preserving Product Integrity*			*Preserving Material Integrity*	
Circular economy strategies	Long Life	Lifetime Extension	Product Recovery	Structural Reuse	Material Recycling
Actions / Processes	Physical Durability Long use Reuse	Repair Maintenance Adapt Upgrade	Refurbishment Remanufacture Parts Harvesting	Repurpose Resize Reshape	Remould Mechanical Thermal Chemical

Fig. 1.3: Framework for circular design of composites (*Joustra et al, 2021b*)

Of the two circular strategies preserving material integrity, structural reuse has priority over recycling in order to retain the most value of the material. Moreover, prolonging the life of the material postpones the need for recycling, granting more time to develop a suitable, feasible and viable recycling solution that complies with the practices of the circular economy, something that is currently still missing.

Fig 1.4: Wind turbine blades without a purpose (*Overhus, 2021*)

1.4.1 The problem

Zooming in on structural reuse it becomes apparent that although there are initiatives and startups that enable preserving the material integrity, they often lack scalability. This is a problem because manufacturers are producing wind turbines in mass quantities, and they therefore need to be reprocessed on the same industrial scale too. Joustra et al. (2021b) was, based on certain curvature tolerances, able to structurally reuse approximately 55 wt% of the blade by obtaining standard elements (planks, beams) through segmentation. This makes a clear and broad application of the material possible. However, this has left 45 wt% of the blade, parts that do fall within the curvature tolerances, untouched. As intuitively visualised in figure 1.5, applications that also incorporate these unconventional / curved elements are often one-off projects, none of them are on large scale (applications are elaborated in appendix B. **Therefore, 45 wt% of a wind turbine blade is still in need of a well-defined structural reuse solution, one that facilitates scalable applications.** This offers chances for improvement of the circularity of wind turbine blades.

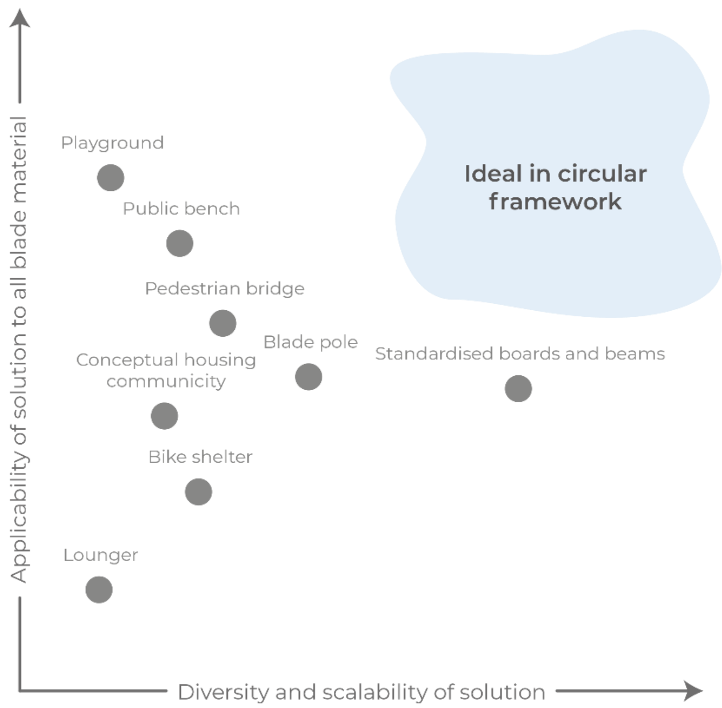


Fig. 1.5: Visualising the room for improvement in structural reuse.

1.5 Scope of the project

Wind turbine blade composites can make use of thermoplastic or thermoset material. Because of the urgency of developing a solution for the current wind turbine blade waste stream, the focus in this research will be on thermoset material; the material that is currently by far the most common. This is elaborated more in chapter 2.3.1.3. Nevertheless, the outcome can be of interest to possible future thermoplastic wind turbine blades too; investigating options to preserve the material integrity can lead to valuable insights and shed light on the physical and material considerations for future blade design of both thermoset and thermoplastic blades, ultimately leading to a more circular blade design that will enable re-use.

What makes a resource widely applicable are among others (great or above average) mechanical and/or physical properties, the possibility to customise it (resize, reshape, recolour, etc.) or the absence of variance (standardised dimensions or shapes). Especially the latter is a limiting factor for reuse of composite material because their original application is often in uniquely and complex shaped products. In the case of wind turbine blades this gives a diverse range of curved elements.

Besides, wind turbine blades, and therefore the elements retrieved from the blades, for a large part consist of sandwich structured composites with a thermoset matrix material. This provides the elements with high (bending) stiffness and high strength, but simultaneously impede the ease of reducing the material and shape complexity.

1.5.1 Knowledge gap

An approach to possibly overcome this is **splitting the sandwich panels** into the two panels of which it is built up. The material properties of a single laminate layer are different from a sandwich structured composite, potentially allowing for more design freedom and thus potentially facilitating large scale application. However, the exact chances this brings is unclear. Moreover, it has not yet been well defined what it requires to delaminate these sandwich panels; separate the laminate from the core material. These are the two knowledge gaps identified for the project.

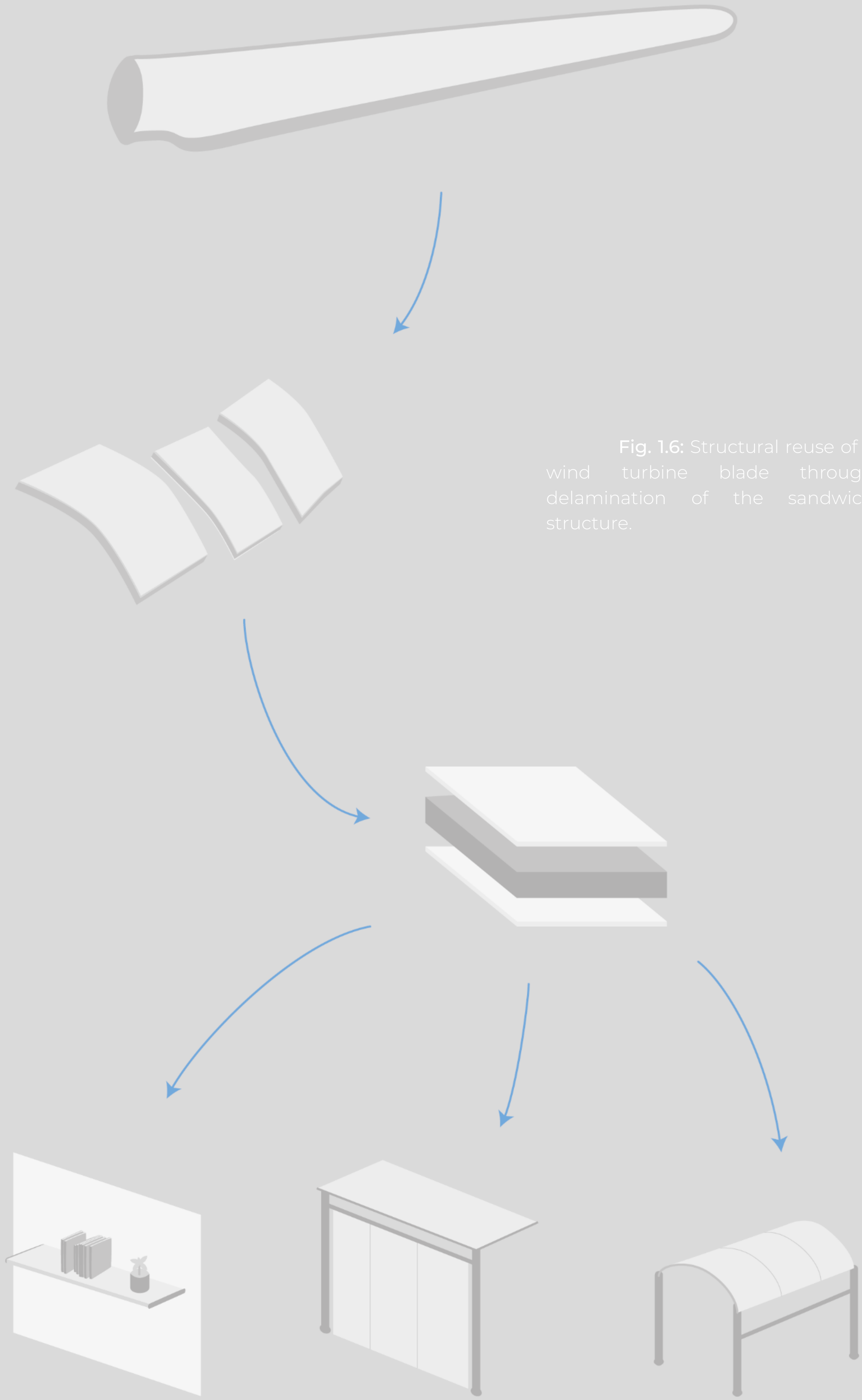


Fig. 1.6: Structural reuse of a wind turbine blade through delamination of the sandwich structure.

1.5.2 Mission

Aside from gaining scientific knowledge on the identified knowledge gap which can contribute to the development of more circular methods within the composite industry, the goal is also to get that process started. Therefore, with regards to the project and its purpose, the following mission has been formulated:

"Creating awareness and stimulating stakeholders to act on the importance of circularity in a wind turbine blade's life cycle by exhibiting the possibilities and the potential of reuse at scale."

The stakeholders are defined and prioritised as: **1)** designers, **2)** manufacturers of wind turbine blades, **3)** operators (owners of the wind turbines and wind parks) and **4)** the general public. The prioritisation is based on their ability, significance and the potential of contribution towards a solution for the problem.

Creating awareness can be understood as offering information to make people understand the current situation with the goal that they will recognize and acknowledge that something needs to be done. If that goes well, they are incentivised to facilitate or contribute to a solution which consequently is also part of stimulating stakeholders. Stimulating stakeholders is moreover defined as lowering the threshold to take action by providing the stakeholders with the right tools and knowledge.

Large scale can either be achieved by implementing the material in a diverse range of different designs or implementing it in a single design that is produced in large volumes. Because of not wanting to restrict the reuse of the current and future end-of-life material to a specific design without knowing what the exact needs, context and developments in the future might be, this project focuses on the first: trying to facilitate more diverse reuse applications of the material through a systematic approach. This has the aim to generate demand for the material at all times so that it can be reused in volumes similar to with what they enter the market, and to a scalable extent.

1.5.3 Research questions

The project can be summed up in the following design assignment: I will design an application for the reuse of composite materials from wind turbine blades on an industrial scale, stemming from a systematic approach that can facilitate this. Focus will be put on the curved elements of the blade and what possibilities the delamination of the sandwich panels enables. This will help provide insights on the previously mentioned knowledge gaps as well as be a means of creating greater awareness around the topic. This revolves around the following formulated research questions:

1. What section(s) of the wind turbine blade is the focus of this project

a. What are the shapes and sizes of this section?
b. What are the material properties of this section?

2. What are the characteristics of the elements retrieved

a. What are the potential ways of segmenting the blade?
b. What are the (maximum) dimensions of the elements retrieved?
c. What is the shape of the elements retrieved?
d. What is the material composition of the elements retrieved?
e. What are the material properties of the elements retrieved?

3. How can the laminates of the sandwich structure be separated from the core material?

a. How is this affected by the characteristics of the product?
b. Which delamination method is most suitable?
c. What is the condition of the material after delamination?

4. To what extent can the shape of the laminates be altered after delamination?

a. What is the type of deformation present during shaping?
b. How will the bending affect the material's mechanical properties?
c. What is the difference in bending behaviour in different orientations?

5. What scalable reuse application for wind turbine blades has the most potential?

a. What market best exploits the characteristics of the decommissioned blade material?

1.6 Methodology

Often systems, services and products are designed out of a necessity for a certain function that it fulfils, or from the urge to provide value to the end customer. In these processes, the resources and techniques used to do so are often chosen with the goal of fulfilling that function in the best way possible or based on certain constraints. However, in the case of this project, it is the other way around and instead of having a solution that needs a material for it to be embodied, the material is the starting point. Yet, there are still many unknowns about the material, its characteristics and the process of retrieving the material. This needs to be investigated first to identify the strengths and limitations to ultimately be able to preserve its value.

In theory, the project is tackled through a double diamond design approach that first explores the material (discover) after which an understanding of the material and its context is created (define). Then, based on the insights and conclusions, possibilities are looked at (develop) which leads to a final suitable reuse application for the material (deliver). In practice, it can be best described as a continuous loop of smaller, not predetermined and more focussed double diamonds, often happening simultaneously and all influencing and building on each other. As a lot about the topic is still unknown, this explorative approach allows for iteration on the research focus through research and ideation outcomes in order to steer the attention towards the most promising outcome. The Circular Applications Through Selection Strategies (CATSS) method is used as a systematic approach to identify secondary applications and determine the most suitable market. This is elaborated more in chapter 6. At completion, the outcomes are evaluated, and recommendations are made.

Additionally, input from 'the outside' through interviews, talking to fellow students and discussion during meetings with the supervisory team spark creativity and help shape the design process as well.

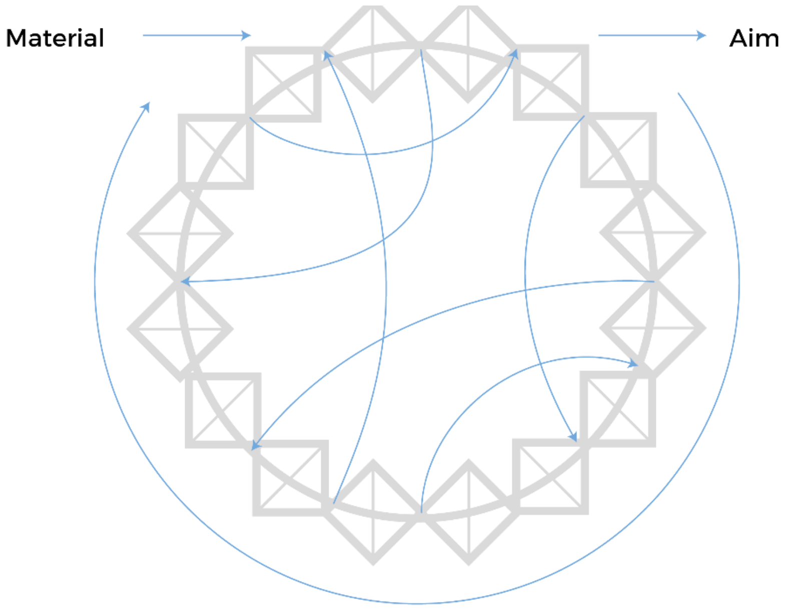


Fig. 1.7: Visualisation of the methodology with a continuous loop of double diamons.

2. A deep dive into a wind turbine blade

Wind turbine blades are manufactured by different companies, LM Wind Power, Vestas, Siemens Gamesa and Enercon to name a few. Exact properties of the wind turbine blade, its material and anatomy are rarely published in scientific literature mainly due to confidentiality issues.

This chapter will dive deeper into the properties of decommissioned blade material by giving an overview of the most probable geometries and materials used of the possible elements retrieved. This is done to define the material in question and answer the first research question.

Fig 2.1: Photo of wind turbine blades (*Depositphotos, n.d.*)

2.1 Reference blade

As previously mentioned, a blade is a self-contained design, no parts are being produced as standardised components which has as a consequence that the design and material composition differs per model. Moreover, as designs are dependent on material properties and vice versa, the development of materials with better mechanical properties might change blade design in the future too. This all makes setting an exact standard as a starting point more difficult. Therefore, for concretisation purposes, besides consulting literature sources, a reference blade has been chosen.

The baseline of a wind turbine blade has been based on the NREL offshore 5MW wind turbine concept model developed by Resor (2013), a turbine with blades of 61.5m long and 17,740kg in weight, and which is extensively used in studies by the wind energy research community as model that represents the current and future state of the art in an offshore wind turbines.

2.2 Design

A wind turbine blade consists of an inboard, midspan and outboard section. The inboard section, sometimes also referred to as the root, connects the blade to the turbine's hub. From the root onwards the blade starts to shape into the air foil profiles for aerodynamic performance that gradually tapers towards the outboard section, or also referred to as the tip. This is a relatively flat air foil profile that is often bent to prevent collision with the tower.

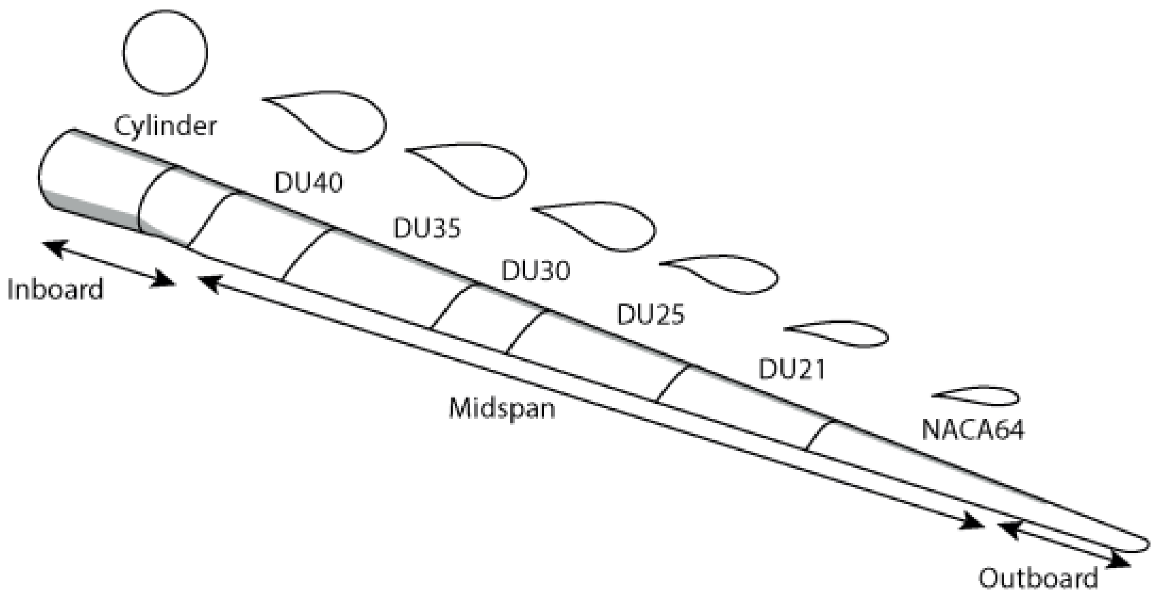


Fig. 2.2: Visualisation of blade with main sections and air foil profiles (*Joustra et al., 2021b*)

2.2.1 Geometry of the blade parts in focus

The 45 wt% of the wind turbine blade in focus of this research is primarily located in the inboard (40 wt%) and outboard section (2 wt%). The inboard is a cylindrical shape of 10m long with a starting chord of 3.386m that increases towards the end. Here it transitions into a DU99-W-405 air foil profile, marking the beginning of the midspan section. This transition happens through an ellipse type shape with the trailing edge flattening at approximately two thirds of the inboard section.

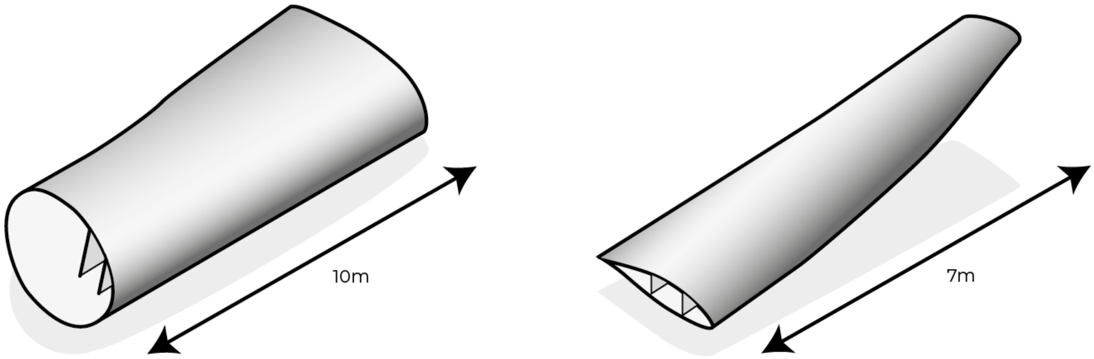


Fig. 2.3: Geometry of inboard (left) and outboard section (right).

The outboard has a NACA-64-618 air foil profile (see figure 2.4) starting at 54.5m of the blade span, running until the tip at 61.5m (total length 7m). The chord and twist at the beginning of the outboard section is about 2.35m and 0.9 degrees respectively, both rather exponentially decreasing to about 1m and zero degrees at the tip respectively. The tip deflection (relative to the end of the midspan section) due to pre bending is predicted to be 1.5 m (*Sartori et al., 2016; Bazilevs et al., 2012*).

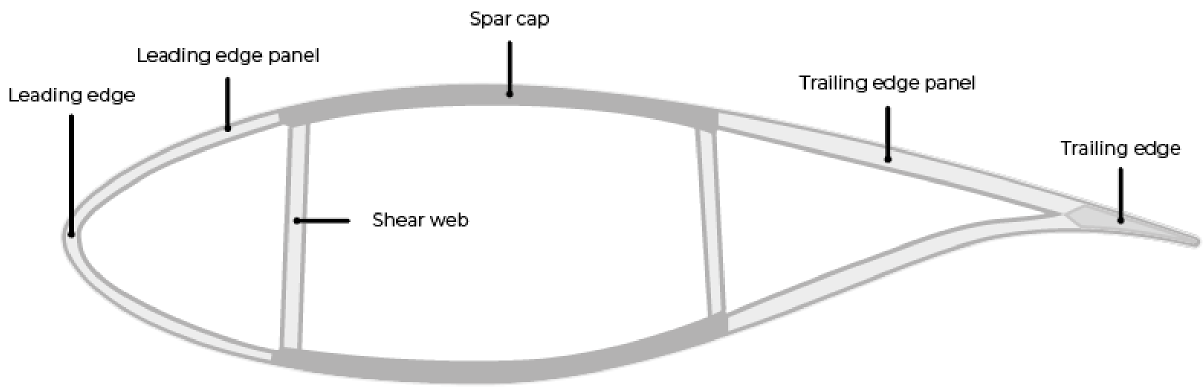


Fig. 2.4: Blade air foil profile

Zooming in on the design of the air foil profiles, there are two different purposes determining the design: aerodynamic and structural performance. Figure 2.4 gives an overview of the elements in an air foil profile. The shear webs (front and rear) begin at a blade span of 1.3667m and end at 60.1333m. Thus, they also run through the cylindrical inboard section. Together with the spar caps the shear webs act as a beam to primarily carry the loads. The leading edge and trailing edge panels provide an aerodynamic shape. These panels, together with the shear webs are made with a sandwich structure. The top and bottom of the blade are manufactured separately and then placed on top of each other with the shear webs in between them.

Key takeaway

The root is cylindrically shaped with shear webs, the tip is air foil profile. The inboard section holds most of the weight fraction in focus of the project. The fact that the air foil is flat might facilitate retrieving relatively flat elements. However, the exponential decrease of the chord might hinder retrieving large standardly shaped elements and the irregular curvature of the tip, including the pre bending, make the potentially retrieved elements more complex.

2.3 Material

As previously mentioned, wind turbine blades are primarily built up out of composite material. A composite material is any material which is produced from two or more materials with notably different physical or chemical properties. In this project, when talking about composites we refer to fibre reinforced polymers (FRP). This chapter will identify the type of material and its properties, in focus of the project.

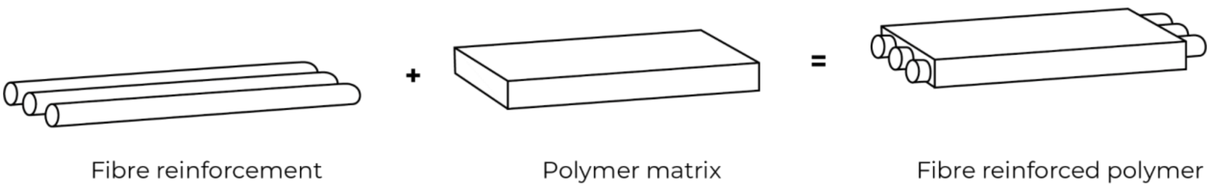


Fig. 2.5: Visualisation of fibre reinforced polymers

2.3.1 Laminate

Fibre reinforced polymers, as anticipated, are made up out of matrix and fibre reinforcement material, the exact type can vary. During a process that is called resin infusion technology, multiple layers of fibre are stacked on top of each other after which they are infused with the matrix material to form a so-called laminate. In the past a manufacturing method using prepreg technology was also sometimes used but due to higher defects risk, lower consistency and worse working environment, this is now only used for repairs (*S. Jansma, personal communication, 7 June 2023)*. Like the name suggests, the fibres provide the main reinforcing elements, they are strong, stiff and light in weight (*Bai, 2023; Motavalli et al., 2010*). The function of the matrix material is to bind the different fibres together so that the stresses are transferred to and from the fibres, and to act as a protective component around the fibres (*Brøndsted et al., 2005; Bai, 2023*).

2.3.1.1 Fibre reinforcement material

The most common fibres used for FRP in the wind turbine blade industry are by far glass fibres (*Effing, 2018; Brøndsted et al., 2005*), more specifically E-glass (*Grande, 2008; Eker et al., 2006*). Table 2.1 gives an overview of possible fibre reinforcement material.

Table 2.1. Overview of possible fibre reinforcement material for FRP (*Effing, 2018*)

Type	Glass fibre	Carbon fibre	Other: Aramid, basalt, polyethylene and cellulose
Application in wind turbine blades	99%	1%	<0.01%

Besides glass fibre, more costly carbon fibre is emerging as a (hybrid) reinforcement in the spar caps to accommodate for the growing requirements of the increasingly longer windmill blades *(Mishnaevsky et al., 2017; Brøndsted et al., 2005).*

2.3.1.2 Fibre orientation

Within a laminate, the fibres can be orientated in different directions. The orientation of the fibres relative to each other has influence on the material properties of the laminate (*Adekomaya & Adama, 2017; Retnam et al., 2014*). For this reason, the exact material properties of the complete laminate can vary, depending on the fibre directions, and is often anisotropic. The number of orientations is correspondingly called unidirectional, biaxial, triaxial, and quadraxial (which is quasi-isotropic).

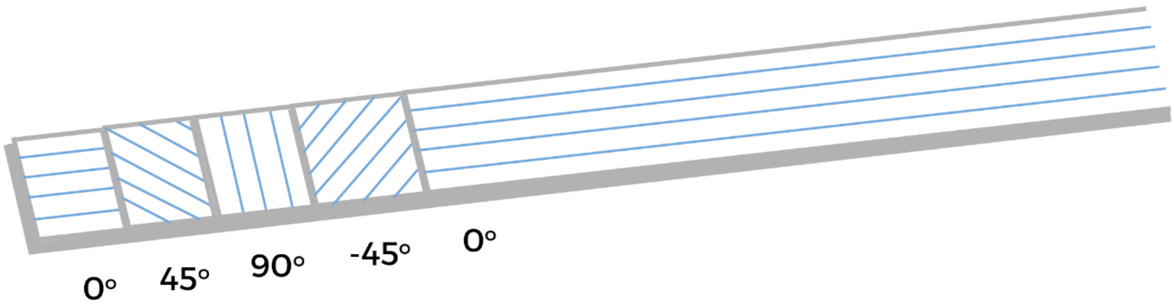


Fig. 2.6: Fibre orientations.

Within a blade multiple orientations are present. Fibres oriented parallel to the direction of the load are the strongest and stiffest. Therefore, unidirectional fibre layers offer the highest strength and stiffness and are for that reason used in the spar caps, a load carrying part. The shear webs are biaxial and the root as well as the entire blade internal and external surface are triaxial (*Resor, 2013; Griffith & Ashwill, 2011).* Because triaxial material has fibres running parallel to the load whereas biaxial has not, triaxial material has a higher strength and stiffness than biaxial material.

2.3.1.3 Matrix material

Although the presence of thermoplastic polymers as a matrix material is growing in recent years and several companies such as LM Wind Power with Arkema's Elium resin (*ZEBRA, 2022*) have shown the possibilities with it, thermoset material is still dominating the wind turbine blade market (*Murray et al., 2017; Yang et al., 2012;*).

The primary difference between the two matrix materials: thermoset and thermoplastic polymers, is their behaviour when exposed to heat. During the curing of the polymers in the manufacturing stage, in contrast to thermoplastics, thermosets form cross-links between the long chains of molecules. As a result, thermosets retain their form and stay solid under elevated temperatures but will eventually degrade above their decomposition temperature whereas thermoplastics melt and are remouldable (*Childerstone, 2022*). This makes it harder to separate the fibre reinforcements from the thermoset matrix at the end of its lifetime and is therefore for a large part responsible for the challenges at the end of a thermoset's composite's life and making material recycling more difficult.

As previously mentioned, the focus of this research is on thermoset composites. Table 2.2 gives an overview of possible thermoset matrix materials. The approximation of the quantity in which they are present has been concluded through literature and personal communication with S. Jansma.

Table 2.2. Overview of possible matrix material for FRP

Type	Epoxy	Polyester	Vinylester
Approximate application in wind turbine blades	80%	19%	1%

With the ever growing size of wind turbine blades, epoxy has become the most common matrix material (*Grande, 2008; Mishnaevsky et al., 2017; Epoxy Resin Committee, 2015*) but a polyester matrix is also still used by manufacturers such as LM Wind Power as although they are heavier, it does not need post-curing (*Richard, 2012; Julie Teuwen, personal communication, 22 March 2023*).

During the manufacturing process the matrix and the fibres come together to form a composite laminate layer. Besides the possible use of different materials, also different mixing ratios are possible (*Brøndsted et al., 2005*). However, although the stiffness, tensile and compression strength might increase with a higher volume of fibres, at a high volume, after 65 vol%, dry areas without resin between fibres might occur, reducing the composites qualities (*Mishnaevsky et al., 2017*). Therefore, the fibre-matrix volume ratio is 60/40 for almost all turbine blades with the 60 vol% being glass fibre and the 40 vol% being an epoxy matrix (*Yang et al., 2012; Papadakis et al., 2010*).

2.3.2 Sandwich structure

The term 'sandwich structure' mentioned in the previous chapter refers to a composite structure where a thick, lightweight and compliant core material is covered by two (or more) thin, stiff, strong and relatively dense laminates, or sometimes also called face sheets or skins, on both sides. These structures enable a high bending stiffness, high strength, and high buckling resistance, while being lightweight (*Thomsen, 2009*) and are therefore very suited for wind turbine blade material. The core separates the two laminate skins that are strong in tension and compression due to the fibres and provide rigidity against buckling and deformation, a similar concept to that of the centre in an I beam (*Stoll, 2014; Ueng, 2003*).

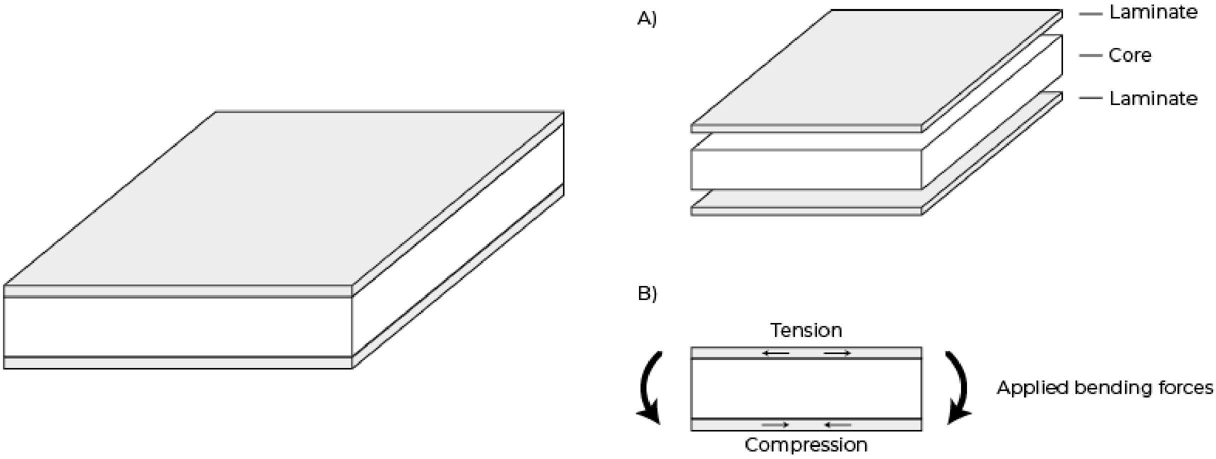


Fig. 2.7: A sandwich structure

2.3.2.1 Core

Within the sandwich structure, the most common cores used in the wind turbine blade industry are inexpensive and robust Balsa wood and low-density foams (*Sloan, 2020; Djemai et al., 2021; Thomsen, 2009*). More specifically, with regards to the foams, PVC has been the primary type used but this has gradually been replaced by PET foam because of better sustainability (*A. ten Busschen, personal communication, 17 April 2023; Julie Teuwen, personal communication, 22 March 2023; S. Jansma, personal communication, 7 June 2023*).

Table 2.3. Overview of possible core material for sandwich composites

Type	Wood	Foam		Other:
	(End-grain) Balsa	Polyvinyl chloride (PVC)	Polyethylene terephthalate (PET)	Honeycomb, cork agglomerate, petiole (date palm), Styrene acrylonitrile (SAN)

In recent years manufacturers have started to employ a hybridised approach regarding the core material, meaning that depending on the specific requirements (weight, structural, production, cost), the core material varies at different locations within a single blade design. Besides a combination of different materials, this can also be in the form of a material in different densities (*Sloan, 2020; Julie Teuwen, personal communication, 22 March 2023*). The difference in density is out of scope for this research.

Key takeaway

The material in question is FRP with glass fibre reinforcement and either a polyester, but most probably, an epoxy matrix material. A large part of the blade, including the part of the blade in focus, contains a sandwich structure with either a Balsa wood or a PVC or PET foam core. These different options give a number of different possible variations in the exact material composition of the retrieved wind turbine elements.

2.3.3 Material disparity along blade's span

As briefly mentioned in chapter 2.3.1.2, the fibre orientation differs for different elements in the blade. Additionally, besides the core material, also the number of layers, and consequently the thickness of the laminate differs along the blade. Therefore, the exact material composition varies along the blade's span, meaning that the location of a retrieved blade element for reuse might have influence on its properties and therefore the reuse possibilities as well as the delamination. To get insight in this, figure 2.8 gives an overview of the different fibre orientations and thickness of the layers and the core material for the different elements of the blade along the blade's span.

Regarding the variation of core material along the blade span, it was concluded that from the root onwards the core is most like balsa wood for the beginning part of the blade as that is where the highest loads are. This shifts into a foam type core for the midboard section and the tip. (*Julie Teuwen, personal communication, 22 March 2023; S. Jansma, personal communication, 7 June 2023*).

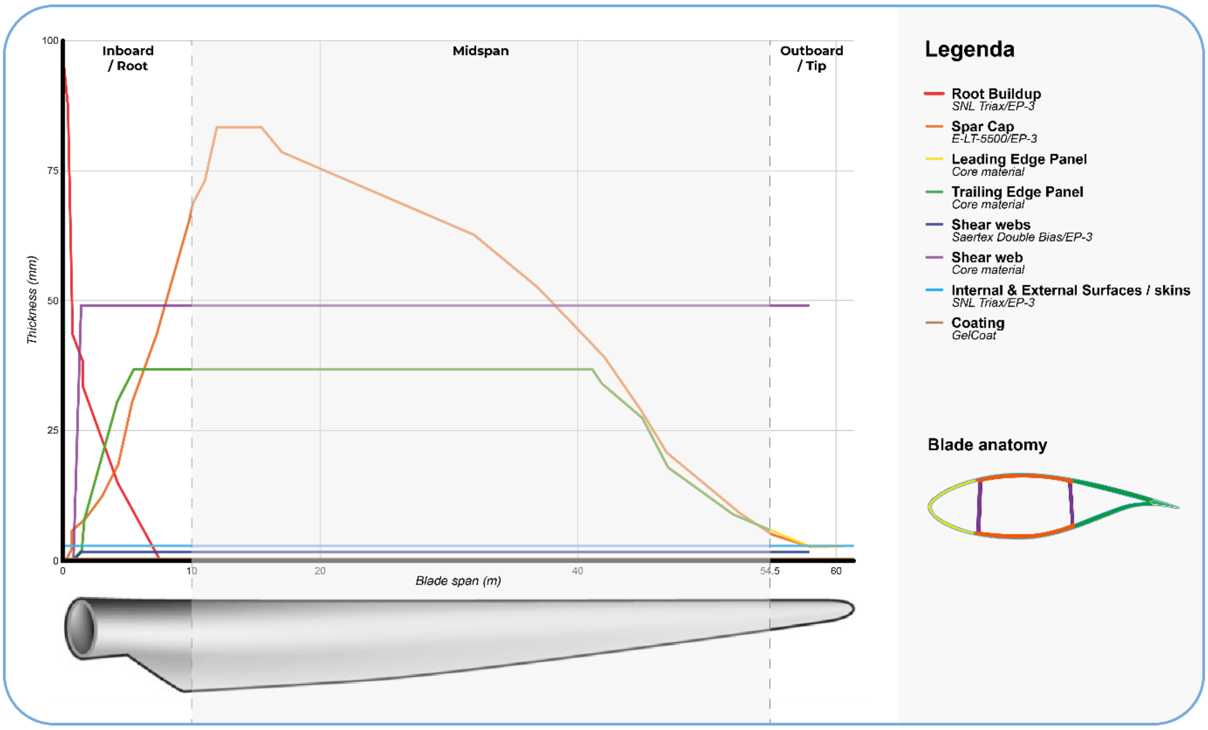


Fig. 2.8: Material overview along blade's span

Key takeaway

The start of the inboard section is a solid triaxial glass fibre reinforced laminate which transitions into a sandwich structure in the leading edge, trailing edge and shear webs, together with an unidirectional monolithic glass fibre laminate for the spar caps as well as an additional reinforcement in the trailing edge. All is covered with the same triaxial glass fibre skin laminate. The outboard section is relatively simpler with a rather constant unidirectional monolithic spar cap and trailing edge reinforcement and a sandwich structured shear web, leading edge and trailing edge panel with a biaxial and triaxial laminate respectively. Because of the absence of a sandwich structure for approximately the first metre of the blade's span, a different approach than delaminating for reuse might be needed.

3. Retrieving elements

The previous chapter has given an overview of the blade sections as a whole. This chapter will dive into the retrieval of elements from these sections for the purpose of structural reuse and identify potential segmentation patterns, the (maximum) dimensions of the elements, their shape and the material composition and thereby answer research question 2.

In order to get an answer to the above-mentioned matters relating to the geometry of the elements, a CAD representing the inboard and outboard section of the blade has been modelled. This model is based on the NREL offshore 5MW wind turbine concept model developed by Resor (2013). However, because in the paper it is considered less critical, they do not go into detail in precisely representing and characterising the root and tip geometry. Therefore, the CAD model is not exact but rather a representative for a 61.5m wind turbine blade, estimated to match the NREL offshore 5MW wind turbine concept model to about 10^{-1}m. Bearing in mind that there is great variety amongst the design of wind turbine blades, this precision is considered sufficient for the purpose of demonstrating the approach used in the project.

3.1 Inboard section

3.1.1 Segmentation

The wind turbine blade is segmented to retrieve usable elements. Following from Joustra et al. (2021b), the cutting losses with the use of a water jet cutter with a diameter of 0.7 mm were found to be negligible. First the boundary conditions for the segmentation of elements are discussed after which the cutting patterns to segment the blade is determined.

3.1.1.1 Constraints

Concluding from Joustra et al. (2021b), the leading edge and trailing edge bond areas are unfit for the recovery of elements due to, amongst others, their mixed material composition, strong curvature and poor physical condition. In this study they have been assumed to be 0.1m (*Resor, 2013*). Additionally, for similar reasons, the first 1.4m of the inboard section has been redeemed unfit for the retrieval of structural elements. More on this can be read in chapter 3.1.3.

Erosion damages the blades. This is most significantly due to water droplets, but also because of sands or salt particles, UV, insects or anything else that might hit the blade during use. As a result, the surface roughness will negatively affect the aerodynamic performance, leading to a reduction in annual energy production (*Slot et al., 2015)*. However, more relevant for this research is that when the coating erodes off, the composite material is left partially unprotected, making the laminate subject to cracks, delamination and damage in general. This erosion typically concentrates at the leading edge, due to the frontal impact during rotation and can occur primarily at the last 25% of the blade span, as that's where the impact velocity is at its maximum (*Verma et al., 2021*). In theory there should be a linear distribution of damage over the blade span due to the linear increase in impact velocity and energy, but it is only observed at the tip. It is theorised that there is a threshold after which the damage starts. (*Interview N Sotelo, personal communication, 6 June 2023)*. Nevertheless, it can be concluded that the potential erosion damage comprises the leading edge of the entire tip and compromises the integrity of the material, making it unsuitable for reuse. It is assumed that this leading-edge damage falls within the 0.1m at the leading edge deemed unfit in the previous alinea.

A transition in the retrieved elements from sandwich to monolithic is undesirable because of the irregularity in the material composition, and consequently the material properties, along the element. A segmentation pattern cutting directly along the spar caps is therefore chosen.

3.1.1.2 Pattern

Following from the constraints, the following segmentation pattern is proposed. The dashed red lines indicate the cutting lines.

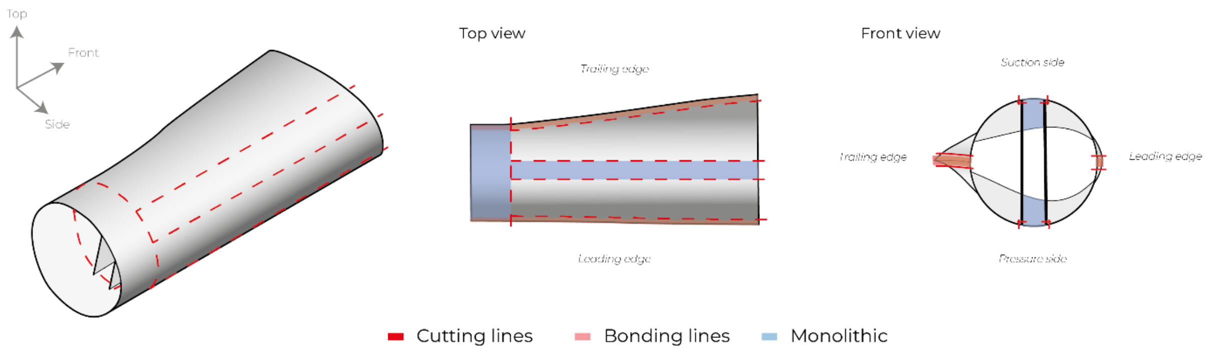


Fig. 3.1: Segmentation pattern for inboard section

Patterning the blade this way gives 8 elements. The shear webs are flat panels with a constant material composition, which is advantageous for large scale reuse applications. This makes them suitable for the segmentation approach demonstrated by Joustra et al. (2021b). Similarly, beam elements can, for example, be recovered directly from the spar cap (*Joustra et al., 2021b*). Additionally, both types of elements are not limited by the length of the inboard section. Therefore, to preserve the material integrity of these elements they will not be the focus of this study.

This leaves 4 elements. In the continuation of the report the retrieved elements in focus of the project will be referred to based on their edge (leading or trailing) and side (pressure or suction).

3.1.2 Dimensions and curvature

Based on the segmentation pattern, the dimensions and curvature of the panels retrieved was measured in the CAD model. Figure 3.2 visualises the length of the elements and their width in the form of the arc length at the beginning and the end, in the context of the entire blade section. The spar caps are assumed to have a constant width of 0.6m (Joustra et al., 2021b).

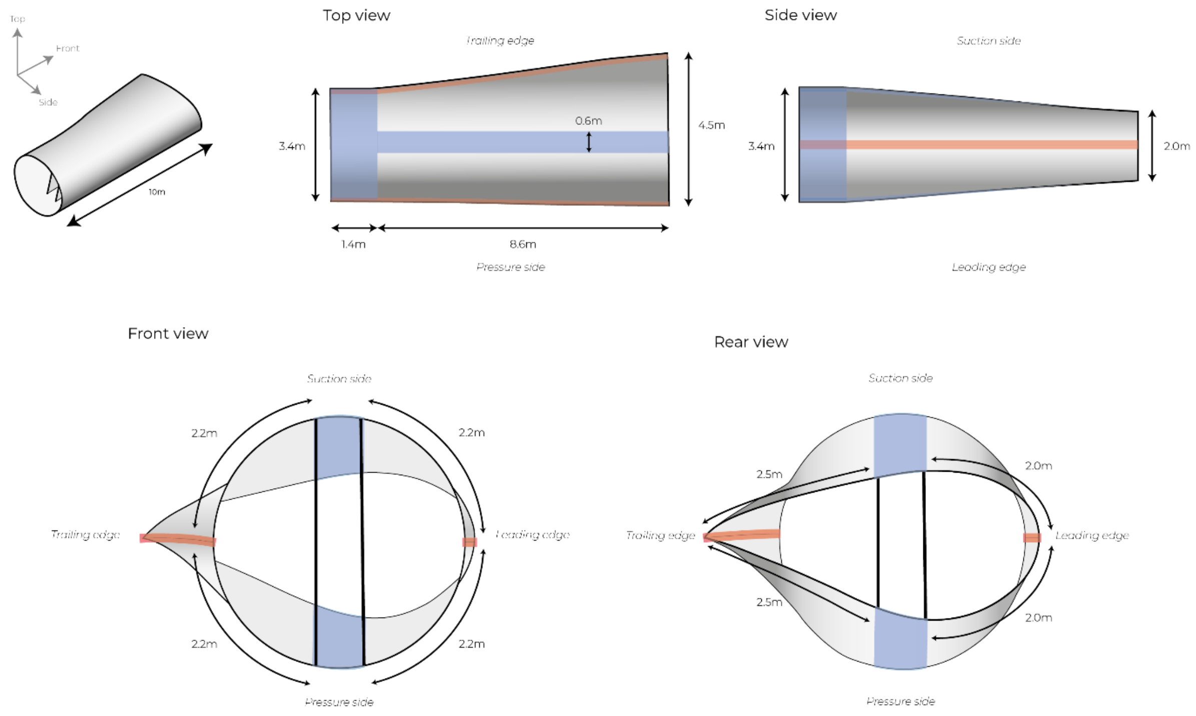
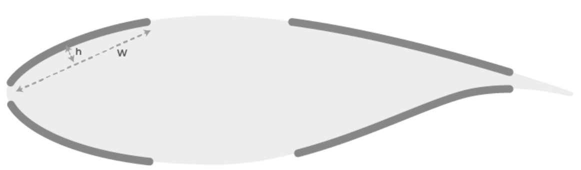


Fig. 3.2: Dimensions of the elements retrieved out of inboard.

The curvature of the panels affects the ease of reuse; higher curved elements might prove more difficult to reuse than relatively flat panels or vice versa. The curvature of the panels has been simplified as arcs with a constant radius.

Fig. 3.3: Measurement from the arc of the retrieved element seen in a sectional view.



Using the measurements derived from the arc's chord in the CAD model, together with the perpendicular bisecting line to the highest point of the arc, the radius of the arc was determined using the formula: $\frac{h}{2}+\frac{W^2}{8h}$. The variables are visualised in figure 3.4.

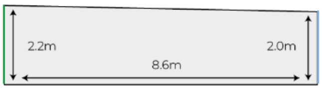
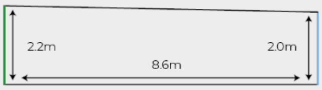
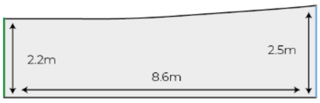
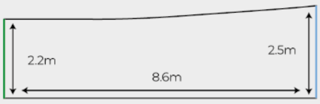
Panel		Dimensions	Curvature	
Leading edge	Suction side			Begin R = 1.7m End R = 1.2m
	Pressure side			Begin R = 1.7m End R = 1.4m
Trailing edge	Suction side			Begin R = 1.7m End R = 5.4m
	Pressure side			Begin R = 1.7m End R = 19.6m

Fig. 3.4: Curvature of the elements

For both the suction and pressure panels from the leading edge the radius of the arc decreases (6cm/m and 4cm/m respectively) along the blade span. This means that the curvature, the deviation from a flat panel, increases. For the trailing edge the curvature decreases (suction side: 43cm/m and pressure side: 208cm/m).

Key takeaway

The max dimensions are different for the leading and trailing edge but are both relatively large. However, because of curvature and manageability of the elements, the panels potentially have to be cut in smaller elements.

3.1.3 Material composition

From chapter 2.3.3 Material disparity along blade's span the material composition of the retrieved elements can be concluded. This is also visualised in the figure 3.5. The leading edge and trailing edge are similar. Up until the point where the shear webs begin (1.4m) the blade's material is solid triaxial glass fibre reinforced laminate which is challenging to cut (*Joustra et al., 2021b*). Also, the root ends tend to be manufactured separately. Therefore, the first 1.4m is not considered suitable for the reuse method in focus of this project and has not been included in the potential retrieved elements.

At the 1.4m point, as the triaxial root laminate is declining in thickness, the Balsa wood core material increases in thickness, up to 5.4m after which it remains constant. From this point it forms a sandwich structure together with the triaxial skin laminate that covers the entire blade. However, as can be seen in figure 3.5, the root laminate and skin laminate overlap for about 7.5 metres on both the leading and trailing edge. Although both are triaxial laminates, the outside laminate of the sandwich structure, starting at 1.4m will therefore start off thicker and decrease in thickness until the root layup runs out. The skin laminate has a constant total thickness of 3mm. With the layer thickness of the triaxial skin material being 0.94mm (*Resor, 2013*), this means a 3 layered triaxial glass fibre reinforced laminate.

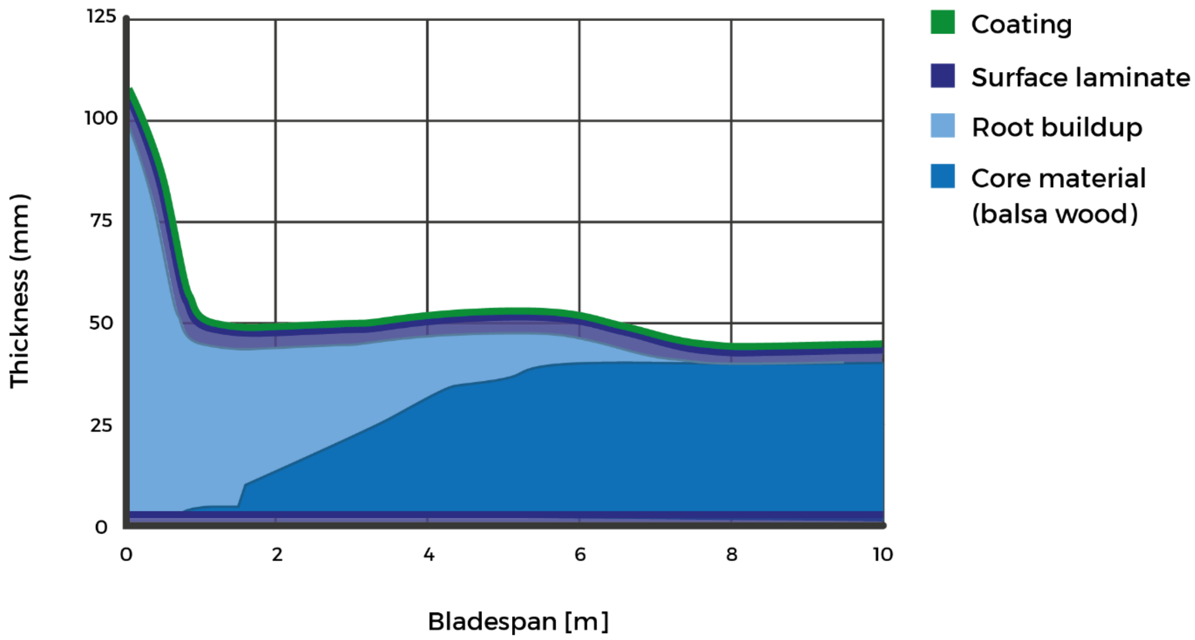


Fig. 3.5: Material composition of the retrieved elements from inboard section.

Key takeaway

The inside laminate has a constant thickness of 3mm, the outside laminate's thickness decreases along the blade up until about 7.5m. It is assumed that it is unlikely that the (increasing) thickness of the core material or laminate itself has a significant influence on the adhesion between the two.

3.2 Outboard section

In this chapter the geometry and material composition of the outboard section, ranging from 54.5m to the tip at 61.5m, is explored.

3.2.1 Segmentation

3.2.1.1 Constraints

The same constraints as for the segmentation of the inboard section which can be read in chapter 3.1.1 apply to the outboard section. However, instead of the first 1.4m of the section being redeemed unfit for the retrieval of structural elements, the last 0.5m of the tip has been redeemed unfit because of the large increase in curvature and uncertainty of the exact material composition.

The shear webs end at 60.1333m but the spar cap, although having decreased in thickness, continues close to the tip. This therefore remains of influence to the segmentation pattern.

3.2.1.2 Pattern

Following from the constraints, the following segmentation pattern is proposed for the separation of the outboard section in usable elements. Again, the dashed red lines indicate the cutting lines.

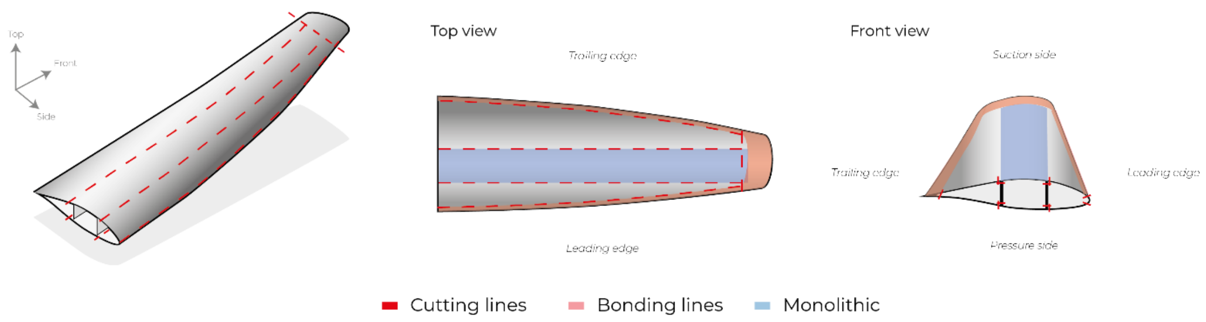


Fig. 3.6: Segmentation pattern

4 elements can be retrieved out the leading and trailing edge on both the suction and pressure side, similar to the inboard section. The maximum width of these elements is again determined by the fact that they are confined between the spar cap and bonding areas at the edges.

3.2.2 Dimensions and curvature

Based on the segmentation pattern, the dimensions and curvature of the panels retrieved was measured in the CAD model. Figure 3.7 visualised the arc length being the widths of the elements, the length of the elements and the 1.5m deflection towards the tip.

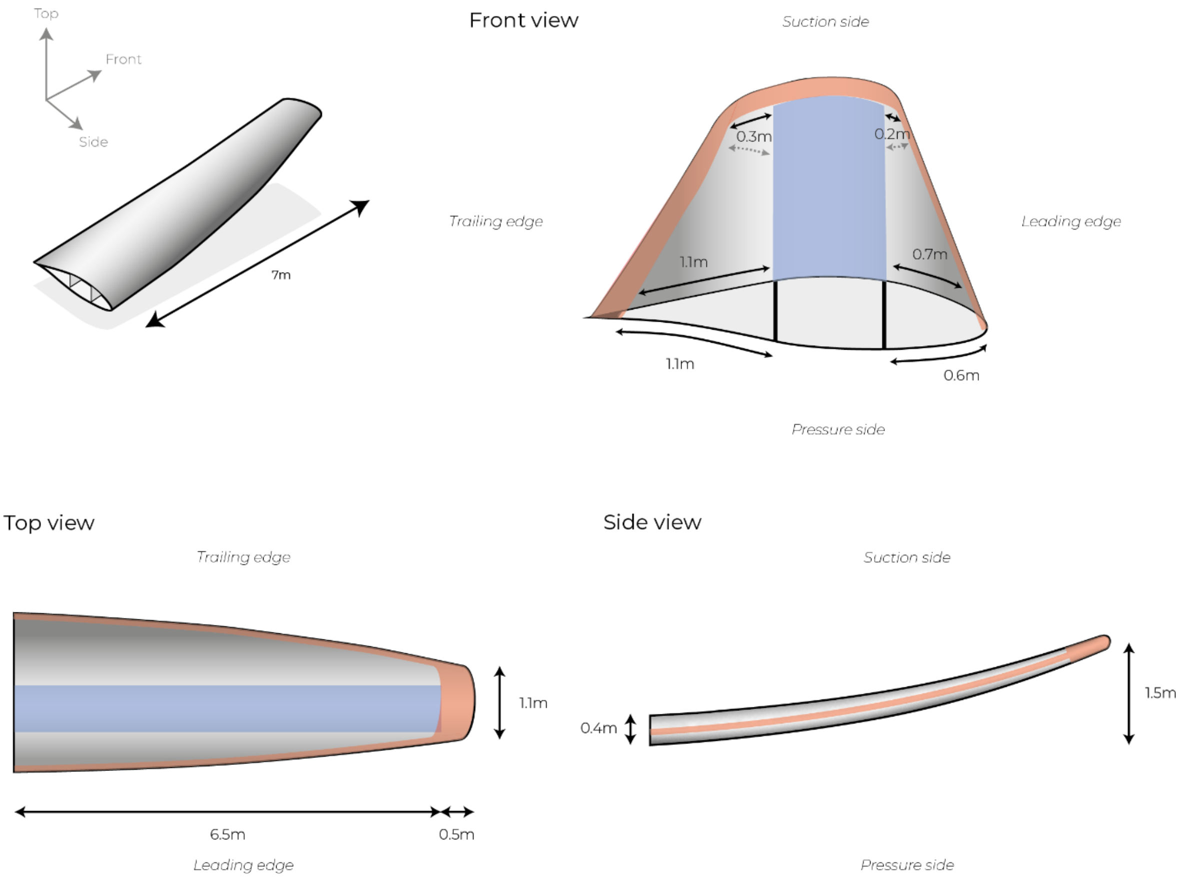


Fig. 3.7: Dimensions of the elements retrieved out of outboard.

Similar as for the inboard section the curvature has been simplified as an arc with a constant radius and determined with the formula as given in chapter 3.1.2.

Panel		**Dimensions**	**Curvature**
Leading edge	Suction side	0.7m, 6.5m, 0.2m	Begin R = 1.1m End R = 0.3m
	Pressure side	0.6m, 6.5m, 0.2m	Begin R = 0.9m End R = 0.2m
Trailing edge	Suction side	1.1m, 6.5m, 0.3m	Begin R = 23.6m End R = 4.2m
	Pressure side	1.1m, 6.5m, 0.3m	Begin R = 5.5m End R = 2.0m

Fig. 3.8: Dimensions and curvature of the elements retrieved out of outboard.

The decrease of the twist angle (average 0.13°/m) has been determined to be a form factor that allows for smooth shaping of the surface, not hindering the recovery of relatively flat shapes (*Joustra et al., 2021b*). However, besides the curvature of the possible retrieved panels along their width (of which the radii are indicated in figure 3.8), there is also a curvature over the length of the panels caused by the deflection of the tip due to pre bending.

Key takeaway
Double curvature due to bending of the width and length of the panels might limit the design freedom in terms of reshaping. The outboard section having a relatively flat air foil profile does not result in the retrieval of flat elements.

3.2.3 Material composition

The material composition of the leading and trailing edge elements retrieved from the outboard are assumed to have a foam core (chapter 2.3.3) and have been based both on the model by Resor (*2013*) which states that the foam in both the leading and trailing edge panels ranges for the same amount of length over the blade span, and the model by Griffith & Ashwill (*2011*) which states that the leading edge foam continues till about 99% of the blade span, which is approximately at 61m. The latter was also described by S. Jansma (*personal communication, 7 June 2023*). The skin laminate is the same as for the inboard section: 3 layers of triaxial glass fibre reinforced material with a constant total thickness of 3mm.

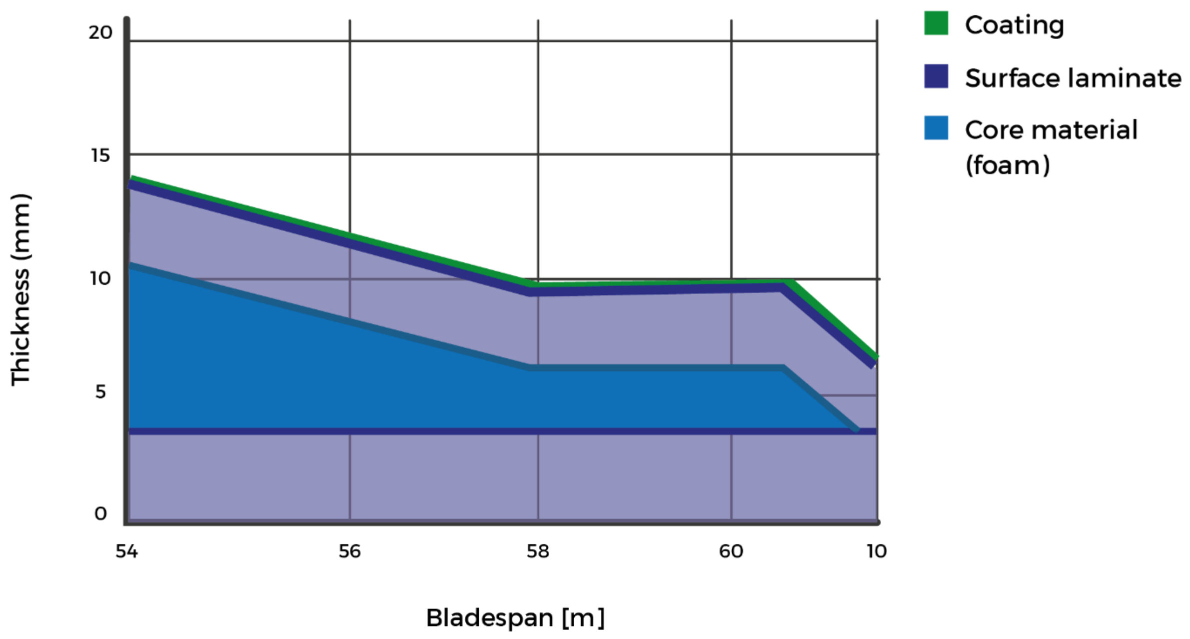


Fig. 3.9: Material composition of the retrieved elements from outboard

Key takeaway
The elements retrieved from the outboard section are made out of a sandwich structure with a foam core decreasing in thickness and a glass fibre reinforced laminate layer with a constant thickness of 3mm on both sides.

3.3 Overview table

A potential segmentation pattern for retrieving elements from both the inboard and outboard section has been determined. The results are the retrieval of different elements with different dimensions and shapes. Table 3.10 combines the results and gives an overview of all the potential elements that can be retrieved with their maximum dimensions, their curvature and where they can be retrieved from. The curvature levels, near flat (r>5m), light (r>2m), medium (r>1.1m), large (r>0.5m) and strongly curved (r<0.5m), have been determined based on construction industry standards (*NEN, 1999*) and divisibility of the curvature radii.

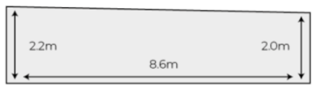
Amount	**Dimensions of element**	**Curvature**		**Retrieved from**	
		Begin	End	Blade section	Edge
2		Medium	Large	Inboard	Leading
2		Medium	Near flat	Inboard	Trailing
1		Large	Strongly curved	Outboard	Leading *Suction*
1		Large	Strongly curved	Outboard	Leading *Pressure*
2		Near flat	Light	Outboard	Trailing

Fig. 3.10: Overview of the potential retrieved elements with their dimensions and curvature

For each element, two laminates can potentially be retrieved on both sides of the sandwich panel (inside and outside). All laminate is made up out of **3 layers** of **triaxial glass fibre material** with a **total thickness of 3mm**. Except for the outside laminates of the elements from the root. Here extra triaxial material from the root buildup increases the thickness, which thereafter tapers along the length of the laminate. Thus, a total of 16 laminates can be retrieved, 4 of which instead of a constant thickness have a thickness that tapers along the length of the laminate.

Table 3.10 gives a clear overview of the material potentially suitable for reuse applications through the method of delamination.

Key takeaway

Larger elements can be retrieved from the inboard section. The given dimensions are for elements that can be retrieved from the section in focus of the project. However, although the width of these panels is mostly determined by the fact that the panels are confined between the spar caps and the edges, the length of panels can extend beyond the inboard or outboard section, into the midspan section. This will allow for the retrieval of larger panels which might be beneficial for the reuse application.

4. Delaminating a sandwich panel

The delamination of a sandwich structure needs to be researched in order to possibly allow for more reuse possibilities because of more design freedom by having a laminate instead of a sandwich structure. This chapter will dive into the delamination, identify the most suitable method to do so and test the feasibility.

4.1 Variables

There are many different variables influencing the adhesion between the laminate and the core material and consequently the ease of the separation process (Saseendran et al., 2017), both on the element properties and separation method side.

Regarding element properties, in the previous chapters it was determined that the laminate is a glass fibre reinforced polymer (epoxy or polyester) that needs to be split from either a Balsa wood or a foam (PVC or PET) core. The exact type of material, as well as the addition of a certain coating or the structure of the core material (e.g., open cell or closed cell) can influence the adhesion. Additionally, the curvature of the element might influence delamination as well. A curved element might pose more difficulty to delaminate than a flat element. Moreover, manufacturing defects, internal stresses or lastly, a high fatigue load that has already exhausted the bond, can be of influence. Due to time constraints as well as the limited accessibility to (a variety in) wind turbine blade material, in this study only a distinction between a foam and balsa wood core is made, the effects of the other element variables remain out of scope for this study.

On the other hand, there is the method of separation itself, something for which there are multiple approaches possible. Through consulting literature, quick and easy testing and trial and error, different approaches have been explored with the goal of devising experiments probable of succeeding to delaminate a sandwich structure. More on this can be read in Appendix C. From the preliminary research it was concluded that mechanical separation (wedge, cleavage, peel) showed the most potential and is therefore the most promising to explore further. Environmental influences (e.g., temperature, humidity) were found not to have any influence or be beneficial.

Table 4.1. Overview of variables in scope, potentially influencing the delamination process

Separation		Wedge, Cleavage, Peel
Element	Material	Balsa wood core, Foam core

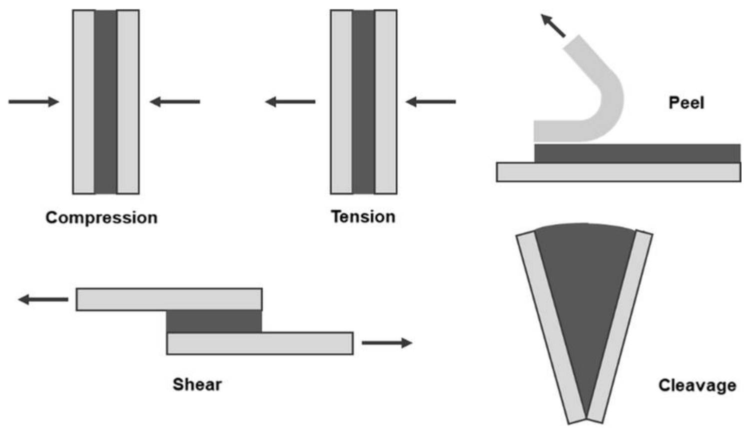


Fig. 4.1. Force orientations for mechanical separation (*(F. A. M. M. Gonçalves et al., 2022)*)

4.1.1 Type of delamination

With regards to the delamination results, 3 potential outcomes, based on different types of failure modes have been identified: adhesive failure, cohesive failure and mixed failure. Adhesive failure describes the failure between the adhesive and one of the surfaces it sticks to. In other words, the bonding within the two materials is stronger than the bonding they have with each other. Cohesive failure describes fracturing of either the adhesive itself or the material that is being adhered. In other words, the bonding between the two materials is stronger than the bonding within the material, resulting in a layer of adhesive or material on the surface of the other material. In a mixed type of failure, adhesive and cohesive failure both happen simultaneously (*Singh et al., 2022*).

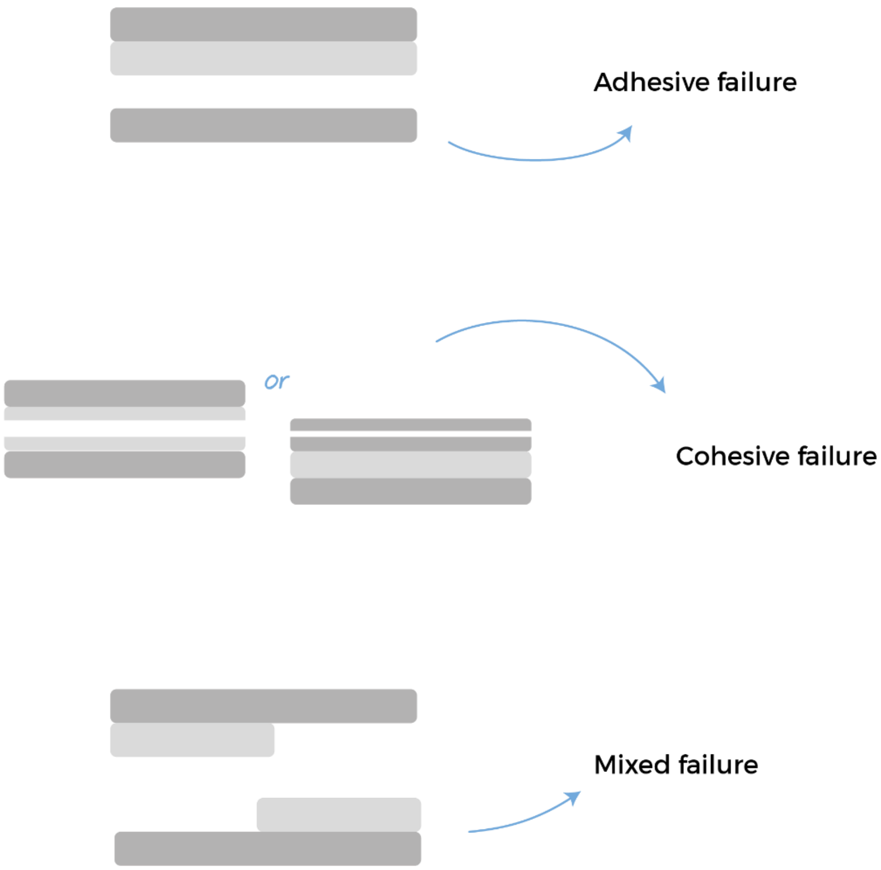


Fig. 4.2: Result of delamination with different failure types

For the purpose of the project adhesive failure would be the most favourable as that leaves the two materials in question: the core and the laminates, the most intact and ready to reuse.

4.2 Experimenting

Based on preliminary research and testing, as described in the previous chapter, the delamination of a sandwich structure through a wedge, cleavage and peel approach, considering different element variables is examined.

Experimenting has been done with smaller pieces of the material. Max dimensions tested were: 200mm by 200mm. The nature of the delamination is assumed to be representative for a larger sized panel. However, future research is needed to substantiate this.

The test specimens were retrieved from the following two sandwich panels. The laminate layers were assumed to be comparable.

1. **Core:** Balsa wood, **Laminate:** 0°/90°/±45° quadraxial glass fibre with epoxy matrix
2. **Core:** PET 115kg/m3 foam, **Laminate:** ±45° biaxial glass NCF with epoxy matrix

Both sandwich panels were manufactured for the purpose of testing their mechanical properties for their use in wind turbine blades. Although they have not been in operation, they are considered representable for wind turbine blade material. Nevertheless, future research is needed to investigate the influence of 20 years in operation on delamination.

Three different methods of separation are tested: wedge, cleavage and peel. With wedge, a sandwich specimen is delaminated by forcing a wedge between the laminate and the core material. This method is tested by hitting a standard wood chisel (blade width: 10 mm) in between the laminate and the core material with use of a hammer.

.

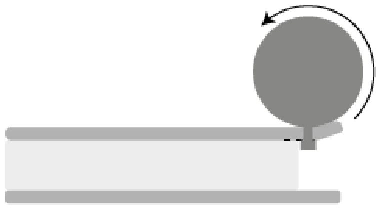
Fig. 4.3: Wedging into the sandwich structure.

In the cleavage method a tensile load is applied to one of the laminates with a pre-crack between the laminate and the core material. This method has been tested by removing about 1cm of the core material to be able to grip the laminate, initiating a fracture along the entire width of the sample of about half a centimetre with a chisel, and pulling on the edge of the laminate layer with the initiated fracture.

Fig. 4.4: Cleavage method

The method of exploiting the weak peel stress is done through a climbing drum peel principle where the end of the laminate is locked onto a cylindrical drum. The drum then slowly but consistently rolls along the sandwich piece and peels the laminate off in the process. This method has been tested by removing about 1 cm of the core material to be able to grip the drum to the laminate, initiating a fracture along the entire width of the sample of about half a centimetre with a chisel, attaching the end of a laminate to a cylinder (r=3cm) and rolling it along the sample. It is important that the radius of the drum is compatible with the flexibility and bending allowance of the laminate and does not induce mechanical defects to the material right away.

Fig. 4.5: Climbing drum peel.



4.2.1 Results and discussion

The laminates of the testing samples did come off the core material with only little force required; it was possible by physical strength. However, although the laminate is the same on both sides for the same core material, a difference in delamination behaviour of the laminates of the balsa wood core for both sides was noted. The outside (recognizable by the smooth surface of the laminate) comes off more difficult than the inside laminate (recognizable by a rougher surface). A possible explanation is a difference in fibre orientation at the surface of both sides of the core material, or that during the production process there are potentially more air bubbles present at the inside laminate than at the outside as air bubbles always want to go up. This as a result could weaken the adhesion. Another theory for this is that during manufacturing of the sandwich panel, the balsa wood core which is attached to a woven material called the scrim is placed in the mould with the scrim facing the inside laminate. Separating the wooden core from this scrim might be easier than from the laminate. The presence and potential influence of a scrim is supported by the fact that on the delaminated inside laminate a woven 0°/90° pattern is visible and on the outside laminate not, see figure 4.6.

Fig. 4.6: Difference in delamination between inside (left, cohesive failure) and outside laminate (right, mixed failure).

The samples with the foam core did not experience this difference. The difference in core material and separation method and its influence on the (result of) delamination will be elaborated further.

4.2.1.1 Type of core material

A difference in the result of delamination between the balsa wood and foam core is noted. For samples with a balsa wood core the delamination primarily happens between the laminate and the core material with sometimes some balsa wood still remaining on the laminate. This indicates that there is mostly adhesive failure with some spots with cohesive failure. Thought, with the foam core delamination happens between the laminate and the core material based on cohesive failure of the core material; there is core material left on the retrieved laminate. Despite there being failure in the core material itself, it does happen right near the laminate, resulting in a thin layer of core material on the laminate. Besides the foam being weaker causing cohesive failure, another explanation could be the possible diffusion of the matrix material into the core. When this cures, this results in a type of mechanical interlocking of the matrix material in the core, strengthening the bond. Similar results were noted by Warriach (*2015*) who in a debonding experiment saw the crack propagating in the foam core 0.5 mm below but parallel to the interface because of the penetration of the resin in the open cells of the foam.

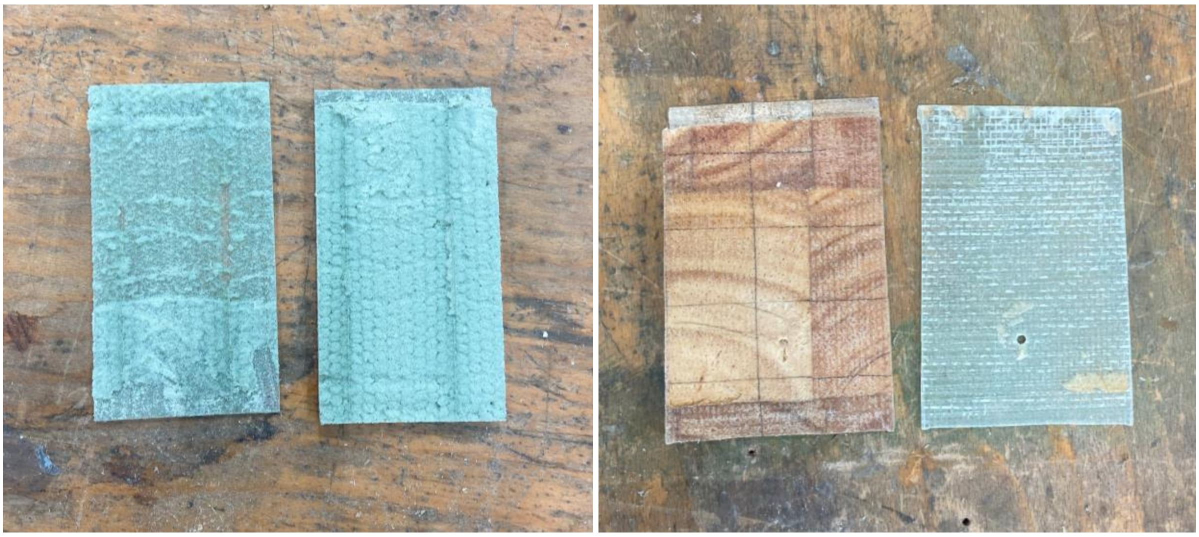


Fig. 4.7: Difference between result delamination foam core (left) and balsa wood (right)

4.2.1.2 Type of mechanical separation

All three separation methods resulted in a delaminated laminate although the process and result were slightly different. The results for exploiting the cleavage and peel are similar, constant and can be done in a fast manner (approximately 10 sec for the largest tested sample), although for the climbing drum peel the speed of the delamination can be more controlled.

Due to the nature of the experiment: the inaccuracy, the method of chiselling and the size of the chisel, the results of the wedge peel experiment were less consistent and clean, and the process took longer (approximately 5 min for the largest tested sample). For the balsa wood core, the chisel sometimes cut into the laminate itself, delaminating the laminate. With the foam core, for some parts the chisel moved between the laminate and the core material and for other parts it cut through the core material itself, leaving spots of core material on the laminate and resulting in a mixed type of adhesive failure. This could be avoided through automation.

What goes for all the methods is that a split between a balsa wood core and the laminate, whether induced by a chisel, cleavage force or peel force, propagates in the form of a crack further between the core and the laminate, whereas for a foam core the crack does not propagate further through the material.

Fig. 4.8: Delamination of laminate itself due to chiselling

4.3 Conclusion on delamination

From the quick and dirty testing as described in Appendix C and the experimenting as described in the previous subchapters, it can be concluded that overall, the laminates can relatively easily be separated from the core material; not a lot of force is required when exploiting the right stresses. Other things that have been concluded:

1 Delamination occurs primarily at the bonding between laminate and core material, as desired. For sandwich material with a balsa wood core this is mostly due to adhesive failure and for sandwich material with a foam core this is mostly due to cohesive failure, leaving core material on the laminates. As a result, the laminates from sandwich panels with a foam core material might require processing after delamination to remove the last bits of foam from the laminate.

2 For sandwich panels with a balsa wood core, there is a difference in delamination behaviour between the inside and outside laminate. For sandwich panels with a foam core there is no difference between the delamination behaviour on both sides.

3 Removing the laminate from the core material without there being a laminate on the other side of the core material is more difficult. Peel or cleavage are more difficult to exploit in this case as there is no normal force countering the peal or cleavage force. With wedging, in the case of both balsa wood and foam material, the core material crumbles.

4 Water has little to no positive effect on delamination.

5 Low temperature (-18 degrees) has little to no effect on delamination.

6 Elevated temperatures above 175 degrees enable easier delamination; the laminate can be easily peeled off the core material. The quality of the material after delamination through this method is unknown but it looks degraded at first glance.

7 Exploiting the peel, using a climbing drum peel configuration is the most promising as this can be done in a fast and controlled manner.

Key takeaway
Overall, the experiments showed the feasibility of delaminating a sandwich panel and it revealed that the result of the delamination process and the type of failure depends on the sandwich structure's core material.

Based on result and practicality, a climbing drum peel method, exploiting the low peel stress resistance of the sandwich panels is the most promising for the retrieval of laminates. In large scale use, the drum can roll over the entire curved surface of the element in one go and relatively easy peel of the laminate. Whereas for cleavage, a lot of room to move is required to pull the laminate in one go is. Readjustment every time you delaminate a part is probably necessary. A wedge might face difficulty in large scale applicability. Although it could be industrialised through means of an idea similar to for example a cheese slicer, double curved surfaces might pose problems.

4.4 Post processing

After the process of delamination post processing of the laminates is required. This is necessary because, depending on the deemed application, the laminate might not be suitable for direct reuse yet as, for example, there might still be core material or coating present on the laminates. Post processing the laminate material after delamination has not been in focus of this research, but this chapter will discuss some thoughts and recommendations about the matter.

The post processing might be more extensive for some applications than others. As an example: applications that seek acoustics might benefit from the core still being attached to the laminate and a design that calls for privacy might see the coating as an advantage. The feasibility for such examples needs looking into as it is unknown whether, for example, the core and/or coating remains of value after the delamination process or survive the manufacturing process of the reuse application.

Nevertheless, from the research into the delamination of sandwich structures it was concluded that as a result of cohesive failure, foam and sometimes bits of balsa wood are left on the laminate. In order to obtain a pure laminate this needs to be removed. This could be done through mechanical processes like sanding, scrubbing, cutting or sawing, or potentially through the help of heat. Scraping has been tested and appeared to be promising but it is unknown how it compares to alternatives. Future research has to determine which method is the most appropriate. The same might be applicable to coating and/or paint that might still be left on the laminate. As previously mentioned, the status of this coating/paint and whether it has not cracked, deteriorated or come loose during the process of coming to a laminate, is not known and too needs more looking into.

Something that requires consideration are the edges of the laminates. The fibres receive a protective coating when it is drawn to better bond to the matrix material but also to protect against the influence of air, moisture and other chemical contaminants (*Eker et al., 2006*). However, to obtain sandwich or laminate panels out of the full wind turbine blade the material is cut, leaving the cutting edges exposed. Therefore, to preserve the desired performance of the material, a new layer of coating needs to be applied to the sides during post processing.

In drawing things to a close it needs to be noted that from a circular economy point of perspective, preferably the reuse application is one for which there is little post processing necessary and to preserve the value of the original material as long as possible. More on this is discussed in the discussion.

5. Material properties

The geometry of the elements, the material composition and the feasibility of retrieving separate laminates from a sandwich structure has been determined. In this chapter the material properties of the elements are researched in order to know what the material's potential and limitations are with a view to potential reuse applications. Also, the effect of bending the elements on the material properties is explored.

5.1 Material properties

Through literature research the material properties of glass fibre reinforced polymer with epoxy matrix were defined. The values are retrieved from the blade design specifications from the model by Resor (2013) and Ansys GRANTA EduPack (2022) Level 2 GFRP, epoxy matrix. Table 5.1 lists the material properties, their value and what it entails relative to other materials. As discussed in chapter 2.3.1.2, the mechanical properties are fibre orientation dependent. The first six mechanical properties in table 5.1 apply specifically to triaxial GFRP and the fracture toughness is retrieved through level 2 GFRP, epoxy matrix in Ansys GRANTA EduPack. For the flexural properties, the UD values in normal and 90° rotated (transverse) orientation are given. This is because although the orientation of the fibres runs along the length of the blade, when retrieving elements out of it, the fibre orientation might run perpendicular to the length or largest curvature of these elements (see figure 5.1). As previously mentioned in chapter 2.3.1.2, this has an influence on the strength, but it also has an influence on the bending properties of the material. More on this is discussed in chapter 5.2. The values have been estimated as the average between minimum value of level 3 epoxy/S-glass fibre from Granta EduPack, as that had values in both 0° and 90° direction, and the comparison of flexural properties for different fibre orientations by Naresh et al. (*2017*).

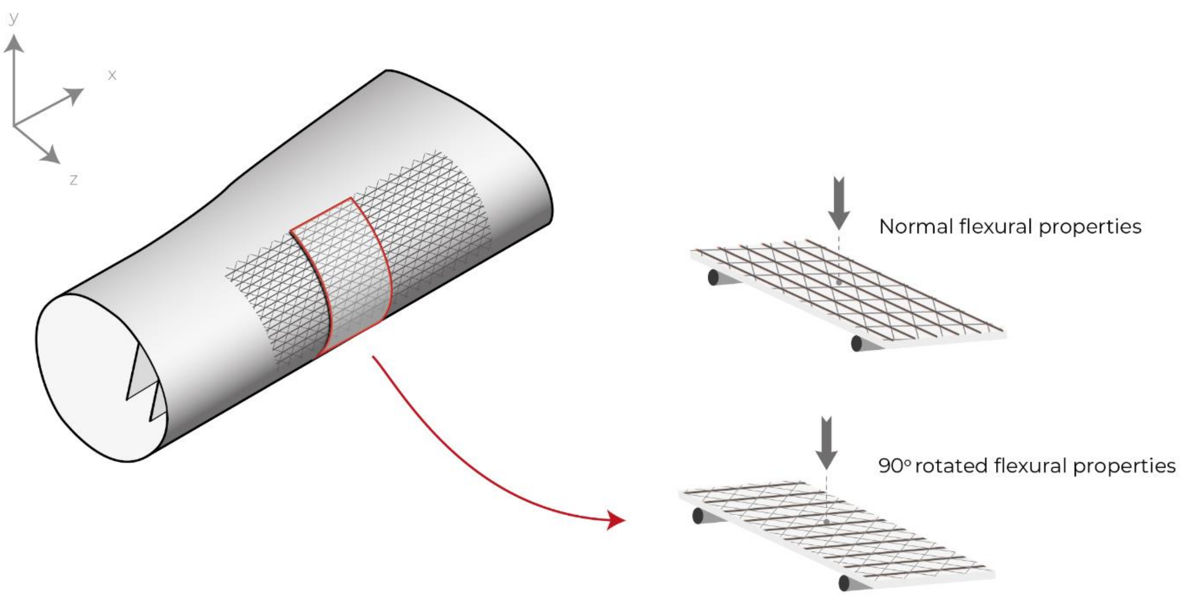


Figure 5.1. Difference in flexural properties over different fibre orientations

With regards to the thermal properties, it is the matrix material that limits the service temperature and processing conditions. The transparency is dependent on the presence of core material and/or coating on the laminate, the table considers purely the glass fibre laminate.

Table 5.1. Properties of triaxial GFRP material from wind turbine blade elements.

Property	Sub-property	Value	Conclusion
Mechanical	Density	1850 [kg/m^3]	Low weight
	Young's modulus	27.7 [GPa]	Stiff material
	Shear modulus	7.2 [GPa]	High
	Poisson ratio	0.39 [-]	Average
	Tensile strength / yield strength	0.7 [GPa]	High
	Compressive strength	0.3 [GPa]	High
	Fracture toughness	1,93e7 - 3,1e7 [Pa.m^0.5]	High
	Flexural strength 0°	1.3 [GPa]	High
	Flexural modulus 0°	37.4 [GPa]	High
	Flexural strength 90°	74.3 [MPa]	Medium
	Flexural modulus 90°	8.7 [GPa]	(relatively) high
Thermal	Glass transition temperature	99.9 - 180 °C	Average
	Maximum service temperature	140 - 220 °C	Average
	Thermal conductivity	0,42 - 0,52 W/m.°C	Low
	Specific heat capacity	1,02e3 - 1,12e3 J/kg.°C	High
	Thermal expansion	8,64e-6 - 3,3e-5 strain/°C	Average
Electrical	Electrical resistivity	2,4e13 - 1,91e14 ohm.m	High, good electrical insulator
Optical	Transparency	Translucent	
Durability	Fresh and saltwater	Excellent	
	UV radiation (sunlight)	Fair	
	In rural atmospheres	Excellent	
	In marine atmospheres	Excellent	
	In industrial atmospheres	Excellent	
	Flammability	Slow burning	Not resistant

The values for the durability of GFRP have been defined by Granta EduPAck and are based on laminates in which the fibres are enclosed within the epoxy matrix. However, cutting the blade into elements creates a cross section in which the glass fibres are exposed. This has been addressed in chapter 4.4.

Key Takeaway

GFRP laminate excels at the majority of its mechanical properties but most notably it is strong, stiff and light in weight. It can also be concluded that the material performs better in tension than it does in compression which is something to take into account when designing a reuse application.

The flexural properties apply to UD material and the exact values will look different for triaxial material. However, it does indicate that the flexural properties are orientation dependent: The flexural properties are less in the orientation perpendicular to the fibres. This is something to take in mind for the design of the reuse application and the process of retrieving the material from the wind turbine blade as bending in the orientation 90° to the blade span will presumably be easier. Because of the presence of diagonal fibres in the form of the +45 and -45 orientation, the difference in the flexural properties in 0° and 90° will most likely be less significant.

The translucent property of the material might offer interesting directions for reuse applications. Also, the material appears to be able to withstand atmospheres with damaging effects of UV radiation, repeated cycles of wetting and drying, the threat of bacterial and insect attack, the prevalence of salts, and high humidity in a good way.

Lastly, the table with material properties show that GFRP has average thermal properties, but most primarily, that the reuse application should be used in an environment below 140 degrees. Also, the fact that the material is flammable might require further post processing action with the material, depending on the reuse application.

5.2 Bending

The scope of the project is based on the fact that there is a difference in flexural properties between a sandwich structured composite and a laminate layer which, when having retrieved a laminate through delamination of the sandwich structure, can be exploited and allow for more design freedom. This chapter will research just how free the more design freedom is and look into the reaction of the material to bending. Moreover, from the flexural properties in different directions the hypothesis is that bending at 90° to the fibre orientation will be easier.

The research questions that will be addressed:

- How far can a laminate retrieved from a wind turbine blade bend?
- Is there a difference in bending behaviour in different orientations?

Additionally, as reshaping or bending a completed laminate risks introducing material defects like fibre misalignment or cracks in the epoxy, the subchapter will dive deeper into the effect of bending on the properties of the material.

5.2.1 Defining bending

Bending is essentially a form of deformation of the material. There are two types of deformation: elastic and plastic deformation. When the material returns to its original shape after the deformation we speak of elastic deformation (the force applied remains below the yield strength) and when the deformation results in a permanent change in shape we speak of plastic deformation (the force applied is higher than the yield strength but below the tensile strength). GFRPs are considered to be brittle with little or no plastic deformation (*Joki et al., 2012; Naresh et al., 2017*), which is further supported by the similar values for the yield and tensile strength of the material (see table 5.1). Therefore, the bending considered in this project is elastic deformation, meaning that once the force is removed the elements will return to their original shape.

The curvature of the retrieved elements has been expressed in the radius of the circular arc of the elements (small radius is large curvature and vice versa). Bending has been established as the change in the radius. The maximum amount of bending is the minimum (or maximum) radius with which the laminate can bend without kinking it, damaging it or breaking it. Initial experimenting with the material revealed that the laminates were able to bend quite extensively and achieve relatively small radii. More elaborate testing determined the minimum bending radius for the laminate along, and perpendicular to the fibre orientation. A full description of the testing, the procedure and the outcome can be read in appendix D.

5.2.2 Result

It was concluded that, regarding the first research question, the laminates can bend to a small radius (32mm). Furthermore, answering the second research question, the orientation of the fibres have an influence on the minimum bending radius; the 90° orientated samples were able to achieve smaller bending radii.

It should be noted that the results are not indisputable. The main goal of the test was to get an insight in the bending properties of the material and the order of magnitude. Future testing with a larger sample size and more variation in size of the laminates is required to gain exact and more detailed knowledge on the bending capabilities of the material.

At the point of failure, there is a slow breakage of the sample. Both sides of the sample remain attached to each other. This is most probably allocated to the fact that it is the matrix material that breaks but the fibres remaining intact as well as the variety in orientation of the fibres; even if some of the fibres break, others in other orientations might remain intact.

Fig. 5.2: Bending samples of the laminate

5.2.3 Discussion

The amount of bending has been determined by establishing the minimum bending radius of a flat laminate and this showcased the flexibility of the material which is potentially interesting for reuse applications. However, it was assumed that the amount of flexibility for bending a flat laminate is the same as bending/flattening a curved laminate; when a flat laminate can bend to a radius of e.g., 50mm, a curved laminate with a radius of 50mm should be able to be flattened. Moreover, the measurements are absolute numbers instead of relative; it might be possible to bend an already curved laminate below the minimum bend radius of a flat laminate. In other words, the minimum bending radius might therefore be proportional to the curvature of the laminate. Additionally, the nature of the tests also neglected the time constraint; the minimal bending radius might be different due to the influence of creep or plastic deformation over time. This was later confirmed when samples were placed in a bended position with a bending radius of 32mm, the defined minimal bending radius, and broke after an unknown amount of time. More on this can be read in chapter 5.3.5. Future research is needed to dive deeper into the bending behaviour of laminates.

5.2.4 Conclusion

Testing revealed that the laminates can bend to a minimum radius of 32mm. This needs to be taken into account in the reuse application. However, because of the nature of the experiment and wanting to reduce the risk of failure, a safety factor of 3 (*Engineering ToolBox, 2010*) is added. This gives a minimum bending radius for the reuse application of 100mm. Additionally, with the maximum curvature of the blade material in focus having a radius of 0.2m, this means that all the retrieved laminates can potentially be flattened and/or bend further to a radius of 0.1m.

Additionally, the bending of the samples (width 60mm) was achievable by hand. Although the force required will increase with the increase of the element width, this demonstrates feasibility for industrial operations.

Further research is needed to find out if there are ways to ease the bending process, what the exact bending force per laminate is and what the influence of creep is.

5.3 Mechanical properties and bending

It was determined that the laminates can be bent. But how does the bending of the delaminated laminates have an influence on mechanical properties of the laminate? A tensile test based on the ASTM D3039 norm for polymer matrix composites has been conducted on the ZwickRoell tensile test machine to determine if in fact bending does influence the mechanical properties by getting insight into the following properties before and after bending:

- Ultimate tensile strength
- Ultimate tensile strain
- Tensile chord modulus of elasticity

5.3.1 Sampling and test specimen

Five specimens per test condition are tested and bent in normal conditions (see figure 5.1). The different conditions:

1. No bending
2. Bending to defined minimal bending radius (32mm)
3. Bending to 2x defined minimal bending radius (64mm)
4. Bending to 3x defined minimal bending radius (96mm)

5.3.2 Specimen size

The specimen width and thickness have been determined to comply with the tensile specimen geometry requirements, with a length that is substantially longer than the minimum requirement to minimise bending stresses caused by minor grip eccentricities, and to promote failure. The ZwickRoell tensile test machine has a maximum test load of 10kN. From Granta EduPack and first trial and error testing it was determined that the tensile strength is expected to be in the range of $2.07*10^8$ Pa - 3.04*108 Pa. The area of the test specimen can therefore be $3.29*10^{-5}$ m^2 at maximum. With a set thickness for the test specimen of 3mm, this means the width of the specimen is 11mm at max.

5.3.3 Specimen preparation

1. A line is drawn across a panel (w=50mm, l=250mm) at l=125mm.
2. The panel is bent along the line. Bending is done by arcing the panel to the required radius and retaining that position for 100 minutes.
3. The panel is visually observed to check whether any abnormalities might occur.
4. Specimens with the required dimensions (figure 5.2) are cut out of the larger panel, keeping the bend line in the middle of the specimen's length.

Fig. 5.3: Samples for tensile tests

Table 5.2. Tensile test specimen properties

Fibre orientation	Width [mm]	Length [mm]	Thickness [mm]
Biaxial ±45° glass (?)	10	250	3

The tests are conducted under room conditions and with a testing speed of 5 mm/min. The loading and data recording is performed by the ZwickRoell machine. The ultimate tensile strength can be calculated with the peak detection force and the surface area, the strain can be calculated using the initial length and the displacement and the Young's modulus is calculated by dividing the difference in applied tensile stress between 25% and 50% of the ultimate tensile strain by the difference in strain between the two strain points.

5.3.4 Results and discussion

Note
Grip failure occurred during some attempts in which the samples shot loose from the grips. These samples were tested again and the average of the two attempts has been taken to balance out the potential effect of shooting loose and loading it twice.

Visual results
The specimen bent to the defined minimal bending radius broke during the bending process. This did not happen directly during the process of bending, but the exact timing is unknown as the specimen was put in a bent position and left unsupervised until 100 minutes later when the specimen would be collected. This is when the sample was found in two pieces, only connected by a few fibres. The sample bent to the predefined minimum bending radius is therefore not included in the results. This however does show that there is indeed an aspect of time involved in the deformation of the laminate.

For the other specimen, no visual abnormalities such as buckling marks, kinks or spots were observed in the material. Also, the lasting curvature after bending is minimal as the specimens after being bent are relatively flat. In other words, the deformation is elastic.

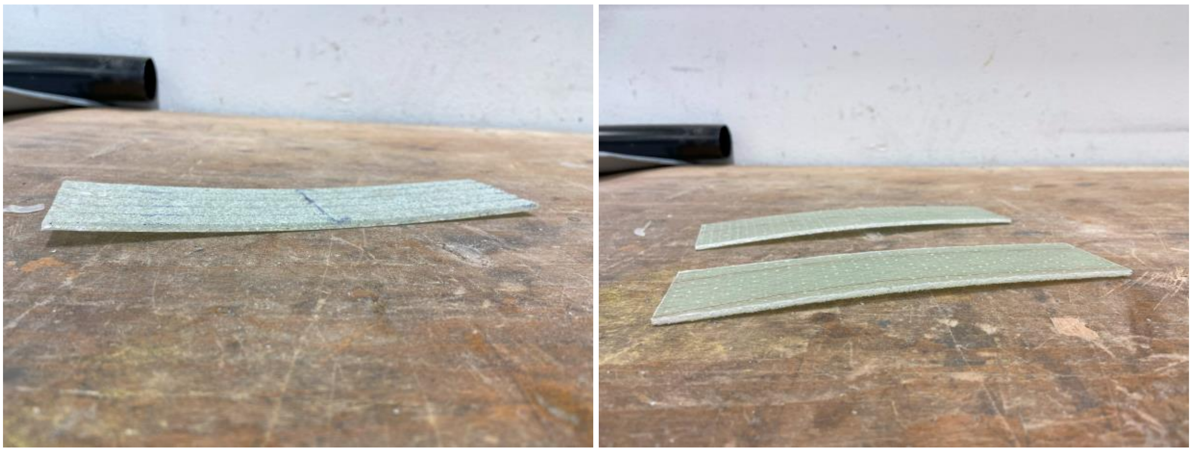


Fig. 5.4: Condition of specimen after bending.

Fig 5.5: broken specimen after bending.

Fig 5.6: Performing a tensile test.

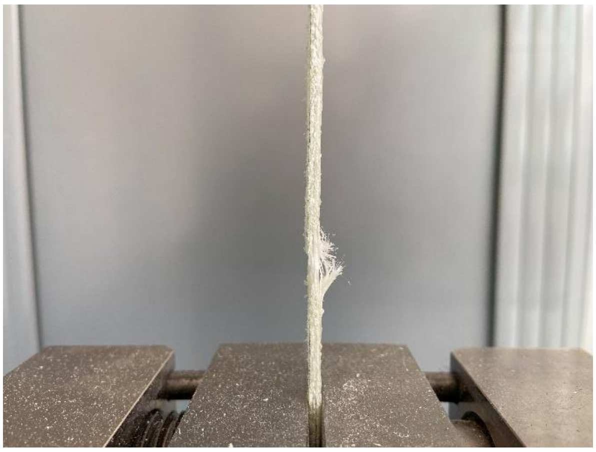


Fig 5.7: A torn GRP specimen

Fig 5.8: The results of applying tension to fives samples.

Mechanical properties

The full raw datasheet on the test results can be found in appendix E. Here the most important findings will be discussed. There is a slight increase in tensile strength with an increase in the amount of bending the samples endured. However, the standard deviation also shows that there is overlap between the sample types.

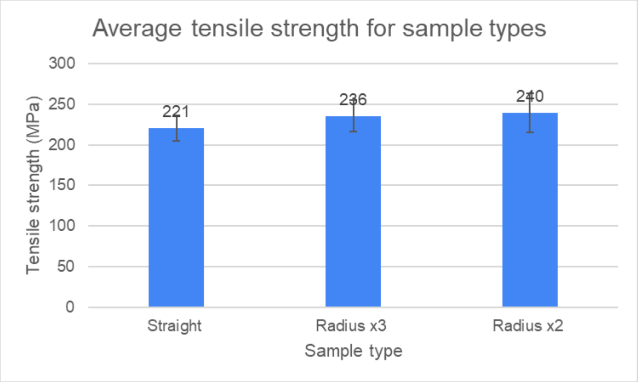


Figure 5.9: Average tensile strength for the different sample types

The average strain is about the same for the different sample types, meaning that all the samples, independent of the amount of bending they endured, can stretch to a similar extent before failure.

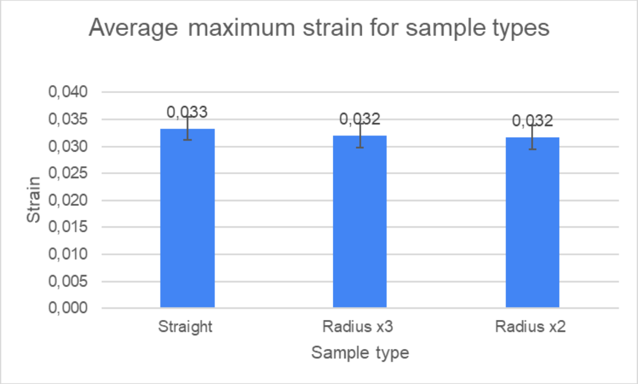


Figure 5.10: Average strain for the different sample types

The average Young's modulus appears to slightly increase with an increase in the amount of bending the samples endured too. Nevertheless, again the standard deviation shows that the numbers are relatively close together.

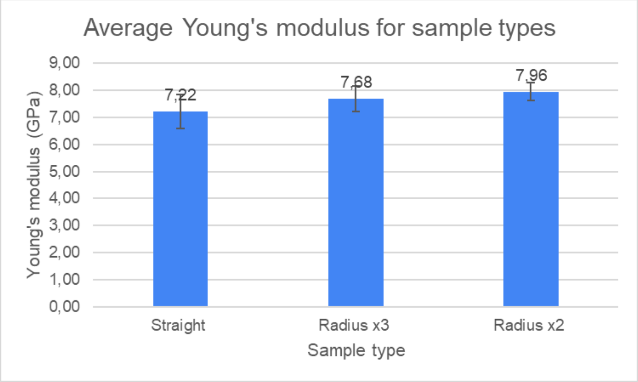


Figure 5.11: Average Young's modulus for the different sample types

5.3.5 Conclusion

The tensile strength and Young's modulus align with the values of biaxial material from the 5MW NREL blade (Joustra et al., 2021b) relatively well. Moreover, it can be concluded that the mechanical properties of the material are not significantly influenced by the bending. Although it appears that there is a pattern of the tensile strength and Young's modulus increasing with the amount of bending the specimens have endured, this increase is negligible.

An explanation for this might be that the samples that experienced more deformation might have encountered some amounts of plastic deformation already, resulting in strain hardening. However, the difference in properties can also be attributed to testing inaccuracies such as better and tighter clamping for the bended specimen.

The goal of the test was to determine whether bending would influence the material properties, which it does not significantly. It can be concluded that the laminates deform elastically and maintain their mechanical properties after bending. This is beneficial for their reuse capabilities: the choice of first reuse application has little to no effect on the following applications. The influence of time and creep and a variance in bending radii as well as fibre orientations need to be investigated further to come to more conclusive results.

6. Ideation / Concept development

The previous chapters have given insights in the material, its geometry, its properties and the delamination process to create an understanding of the material and know what it is capable of. Building on these findings, this chapter describes the process of coming to a suitable reuse application. A CATSS approach (Circular Applications Through Selection Strategies) (*Carrete, 2023)* has been applied as a means to explore the potential of the laminate in a broad variety of markets to come to the most suitable reuse application. This method is characterised by first 1) creating an understanding of the material which will 2) hint at possible reuse options for the material in the form of an initial exploration and then 3) applying the inverse selection method. An understanding of the material has been gathered in the previous chapters.

6.1 Exploration

Through the gained knowledge on the properties of the material and researching ways how these could be exploited a collection of initial ideas came about. Furthermore, building on the material properties by brainstorming with fellow IDE students, talking to experts in the composite and circular design field, talking to people, reading through literature and walking around, more ideas came about which in total led to a compilation of 80+ possible uses for the material. The identified applications were then clustered according to similarities in market sectors. An overview of this can be found in Appendix F.

6.2 Inverse selection

The inverse selection method in short entails determining the most promising market sector by cross referencing the material qualities / properties of the retrieved elements to their relevance to the previously identified markets. This has been done by creating a matrix with the market sectors on one axis and the material qualities on the other. The relevancy of the material quality to the market sector has then been rated on a scale from 1 to 5.

It is hard to quantify the degree as to which the potential market sector makes use of the material properties. It has been assessed by intuition and through consolidation with friends and family. Additionally, sustainability has been added as a decision criteria in the primary step of the ideation process as it is considered essential for the reuse application. Sustainability has been subdivided in the increase in environmental impact it could potentially result in, and the size of the elements used in the market as the larger the size, the more of the material integrity is preserved and more secondary or tertiary reuse options remain possible. Both are assessed on based on instinct and logical reasoning based on the environmental impact and recyclability of current materials used in the markets.

	Material properties													Sustainability		
Potential markets	**Low density**	**High strength**	**High stiffness**	**High toughness**	**Right service temperature**	**Durability**	**Translucent**	**Environmental resistance**	**Chemical resistance**	**Sound isolation**	**Electrical insulator**	**Shape**	**Aesthethics**	**Environmental impact**	**Large size**	**Total score**
Urban furniture	3	4	4	4	4	5	3	5	4	2	3	5	5	2	4	57
Household furniture	3	3	3	3	5	4	3	2	1	4	2	4	3	3	3	46
Interior design	3	4	3	4	5	4	5	3	2	3	2	4	4	4	4	54
Consumer products	4	1	2	1	3	3	2	3	1	2	4	2	3	3	1	35
Sport equipment	5	2	3	2	4	4	1	3	1	1	1	3	2	4	1	37
Gear / equipment	5	2	5	2	4	4	1	3	2	1	1	3	3	3	2	41
Architecture	3	3	4	3	4	5	4	5	4	2	2	4	4	4	5	56
Construction/infrastructu	3	5	4	5	3	5	3	5	5	2	2	4	4	2	5	57
Automotive	3	4	2	4	3	5	2	4	3	2	3	2	1	2	3	43
Transportation	4	4	4	4	4	5	1	4	3	1	2	3	2	3	3	47
Marine	2	2	3	2	4	5	1	5	2	1	1	3	2	2	3	38
Art and Culture	2	1	2	1	4	3	3	2	1	1	1	1	2	1	2	27
Acoustics	3	1	2	1	5	3	1	2	1	5	1	2	2	3	2	34

Figure 6.1: Inverse selection overview

The tallied scores show that the urban furniture, construction/infrastructure, architecture and interior design market score the highest and are thus qualified as more relevant and potentially best exploit the material properties of the blade elements. These markets functioned as the focus of further exploration.

6.3 Scatter plot

More ideas were added to the markets qualified as relevant and others were built upon. To converge from the 35+ ideas across these markets to the most suitable application the ideas were ranked on what was deemed important for the project: preserving the material integrity as much as possible and mass scale application of the material. This has been visualised in a scatter plot (Figure 6.2). The extent to which the idea makes use of the qualities of the material has been assessed based on the same qualities used during the inverse selection method. The size of the application's market has been estimated based on production numbers and their commonness.

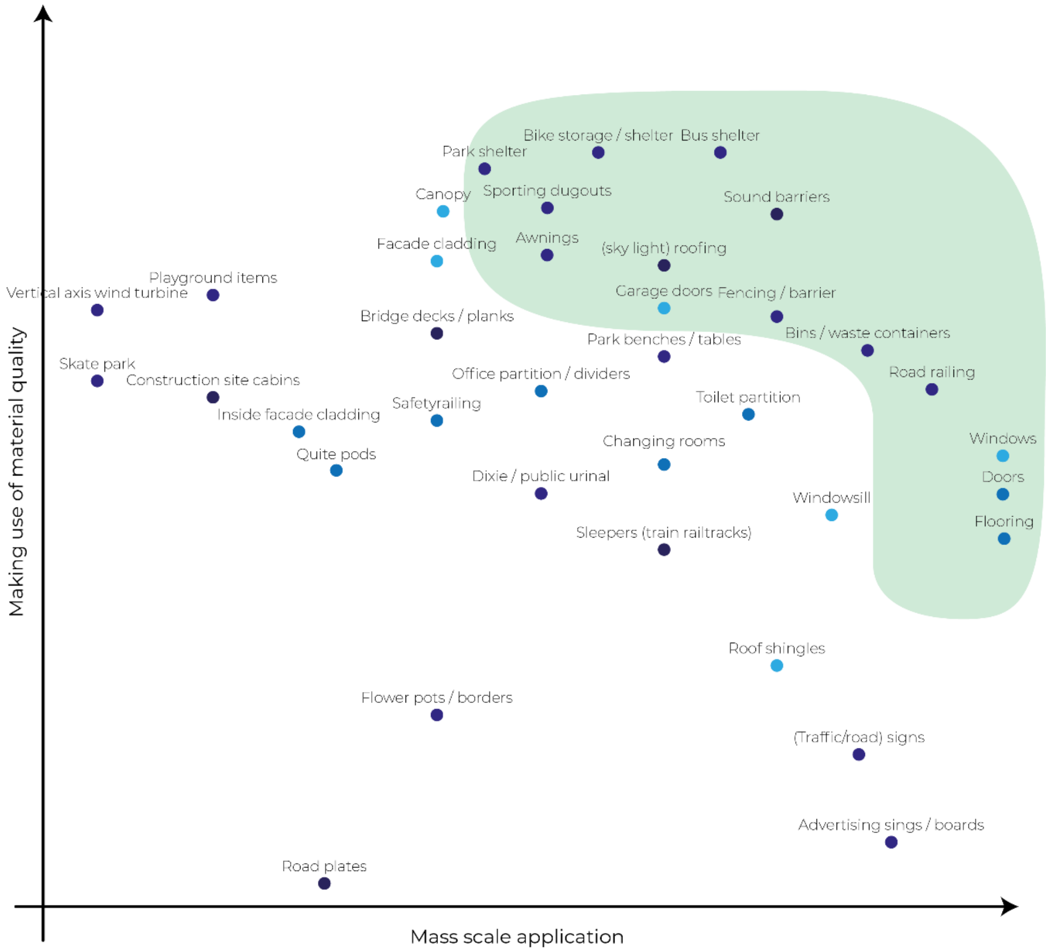


Figure 6.2. Scatter plotting applied to the ideas.

The green highlights ideas that score well on their use of the material qualities or their mass scale applicability and are therefore considered promising.

6.4 Revisiting the mission

After the previous elimination round, still 14 ideas remained. The best out of this selection is chosen by revisiting the mission of the project which was described as.

“Creating awareness and stimulating stakeholders to act on the importance of circularity in a wind turbine blade’s life cycle by exhibiting the possibilities and the potential of reuse at scale.”

However, this is the purpose of the entire project, part of which can be achieved through the realisation of a reuse application. With respect to the goal of the project and building on the research insights, a design vision has been formulated to best describe the intent for the reuse application itself.

“Highlighting the capabilities of reused wind turbine blade material and appealing to the imagination of the viewer.”

The capabilities of the reused wind turbine blade material are defined as its properties and the conclusion of the bending experiments: the added design freedom of the material due to the ability of shaping it. Appealing to the imagination means different things for different target groups. For the general public, who are most likely observers or users of the design, it might generate consciousness about the problem of the linear economy and potential solution. For designers this might mean that it sparks their creativity, and they see other designs possible of making with the material, ways to build on the idea of delamination or new methods of solving other problems. For manufacturers of wind turbine blades or operators of wind parks this might mean that they see the benefit of structuring and documenting their end-of-life material for it to become profitable and for government or large companies they might see opportunities in what to invest in and how reused material would fit in society.

The ideas were evaluated based on the likelihood of inspiring people their capability to showcase the design possibilities. The first is based on personal judgement and the latter was judged on the amount of potential bending and exploitation of the material properties could be incorporated in the design.

Ideas	Park shelter	Sporting dugouts	Awnings	Bike storage / :	(sky light) roofing	Garage doors	Bus shelter	Sound barriers	Fencing	Bins	Road railing	Windows	Doors	Flooring
Evaluation criteria														
Showcasing design possibilities	7	8	4	8	3	2	9	5	3	7	5	3	2	2
Creating awareness / being inspiring	5	7	4	8	4	4	8	5	2	4	3	4	3	2
Score	12	15	8	16	7	6	17	10	5	11	8	7	5	4

Figure 6.3: Ranking of ideas based on vision.

The three ideas scoring the highest are sporting dugouts, bike storage and bus shelters. Because the presence of bus shelters is more common in society which therefore appeals to mass scale and it is believed that more creativity can be put in the design of a bus shelter, it was decided to continue with a bus shelter as a demonstrator for the project.

7. Design of a bus shelter

This chapter will describe the design of the bus shelter using reused laminates retrieved from wind turbine blade material. First, stemming from the research phase, a set of requirements and wishes was drawn up and challenges the design faces are given. Then, through a quick exploration of potential designs, the final design is decided upon, which will be elaborated further. Lastly, the manufacturability and the value of the design is discussed.

7.1 Requirement & wishes

Demands and wishes stating important characteristics that the design should comply with in order for it to work have been listed. They are stemming from both the research phase, standards of governmental bodies and self-proclaimed general functions the bus shelter needs to fulfil. However, most policy regarding bus stops is about the safety, accessibility and layout of the stop itself rather than the bus shelter (*Gemeente Amsterdam, 2015; Provincie Zuid-Holland, 2022*). Therefore, most demands regarding the functionality of the bus shelter itself have been based on the guiding policy principles and preconditions found (*Gemeente Roosendaal, 2008*; *Jacobs, 2019*).

Table 7.1 gives an overview of the most relevant requirements and wishes. The demands must be met, the wishes can help select the most promising idea or design.

Table 7.1: Requirements and wishes.

Category	#	Requirement	Stemming from	Type	Assessment
Performance	1.1	Providing passengers a place to wait while sheltering from precipitation	Own reasoning	Observable	Check design
	1.2	It must exude recognisability, clarity and safety.	Guiding principle (Gemeente Roosendaal, 2008)	Observable	Test amongst people
	1.3	It should be able to withstand forces of maximum wind forces	Own reasoning	Quantitative	Calculation with 12 Beaufort
Dimension and design	2.1	Height (inside) is at least 2.20m	Guiding principle (Gemeente Roosendaal, 2008)	Quantitative	Check design dimension
	2.2	Depth (inside) is between 1.35m and 1.45m	Guiding principle (Gemeente Roosendaal, 2008)	Quantitative	Check design dimension
	2.3	Width (inside) is at least two times the depth	Guiding principle (Gemeente Roosendaal, 2008)	Quantitative	Check design dimension
	2.4	The maximum width (perpendicular to fibre orientation) of a laminate is 2m	Chapter 3.3	Quantitative	Check design dimension
	2.5	The open space between the roof and the top of the walls may not exceed 5cm (due to rain)	Guiding principle (Gemeente Roosendaal, 2008)	Quantitative	Check design dimension
	2.6	There must be a free space between the floor and the underside of the walls to	Guiding principle (Gemeente Roosendaal,	Observable	Check design

		prevent the accumulation of dirt	2008)		
	2.7	The minimum bending radius for the laminates used is 100mm	Chapter 5.2	Quantitative	Check design dimension
	2.8	Rainwater should not be guided to the front of the shelter or the platform	Guiding principle (Gemeente Roosendaal, 2008)	Observable	Check design
Facilities	3.1	A minimum of 2 seating places (seating height: 42-50cm, seating depth: >35cm)	Guiding principle (Gemeente Roosendaal, 2008)	Quantitative	Check design dimension
	3.2	There must be free space (80cm) next to the seat for manoeuvring and setting up a wheelchair	Guiding principle (Gemeente Roosendaal, 2008)	Observable	Check design
	3.3	Have an information window (height: 1.05m, width: 1.15m)	Guiding principle (Gemeente Roosendaal, 2008)	Quantitative	Check design
	3.4	Have lighting	Guiding principle (Gemeente Roosendaal, 2008)	Observable	Check design
Risk mitigation	4.1	The laminates should not be flammable	Chapter 5.1	Observable	Check design
	4.2	No holes are created in the laminate material to preserve the strength and integrity of the material	Own reasoning supported by Gupta et al. (*2023*)	Observable	Check design
Category	#	Wish	Stemming from	Type	Assessment
Material properties	5.1	The edges of the elements are preferably protected to the outside atmosphere through either a coating or a cover	Chapter 5.1	Observable	Check design
	5.2	Exploit tension over compression	Chapter 5.1	Observable	Check design
	5.3	Exploit stiffness and strength with right fibre orientation	Chapter 5.1	Observable	Check design
Design	6.1	Display both bending and flattening of the material	From vision	Observable	Check design
	6.2	Make origin of material clear	From vision	Observable	Check design
	6.3	Allow for mass scale production	From mission	Observable	Check design if it is not too complex

7.2 Challenges

Besides complying to the requirements, two challenges have been identified with regards to the design of the bus shelter and the use of GFRP laminates as a material.

Firstly, the project is about making use of the added design freedom the delamination of sandwich panels gives by elastically deforming the laminates. However, elastic deformation entails that force should continuously be applied to the laminate because otherwise it will return to its original shape. In other words, the laminates need to be permanently fixed in the design. Additionally, this 'locking of the laminates into shape' needs to be done properly and avoid shooting loose as this might create dangerous situations.

Secondly, bus shelters are often the target of vandalism; news items about destroyed bus shelters are too common. It is therefore the challenge to either make them better resistant to vandalism or make them less attractive to destroy.

Fig. 7.1: Example of vandalism at bus shelters (*Huurdeman, 2020*)

7.3 Road to final design

Different designs for a bus shelter have been considered to explore different angles to approach the wishes. A few conclusions were made:

1) Cutting a laminate halfway, bend one half and flatten the other is a promising means of showcasing the design freedom.

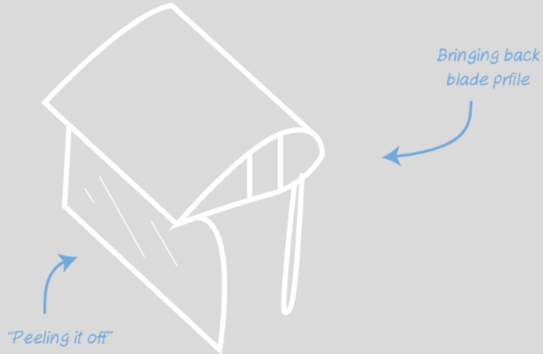
2) Creating a seat out of laminate that is attached to the roof is a promising means of exploiting the tensile strength.

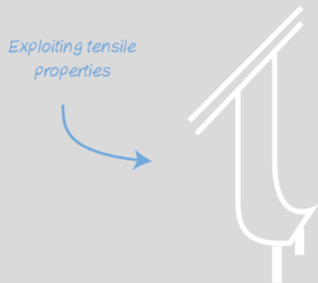
3) The use of greenery is believed to have many advantages (*Dorrestijn, 2019*), it might even discourage vandalism.

4) The origin of the material does not necessarily have to be made clear through a structural part but can also be conveyed through visuals, text or aesthetics.

5) Designs that are too complex detract from large-scale production and the feasibility for the making of a demonstrator.

Based on the iterations, a design has been made.





7.4 A bus shelter from wind turbine blade material

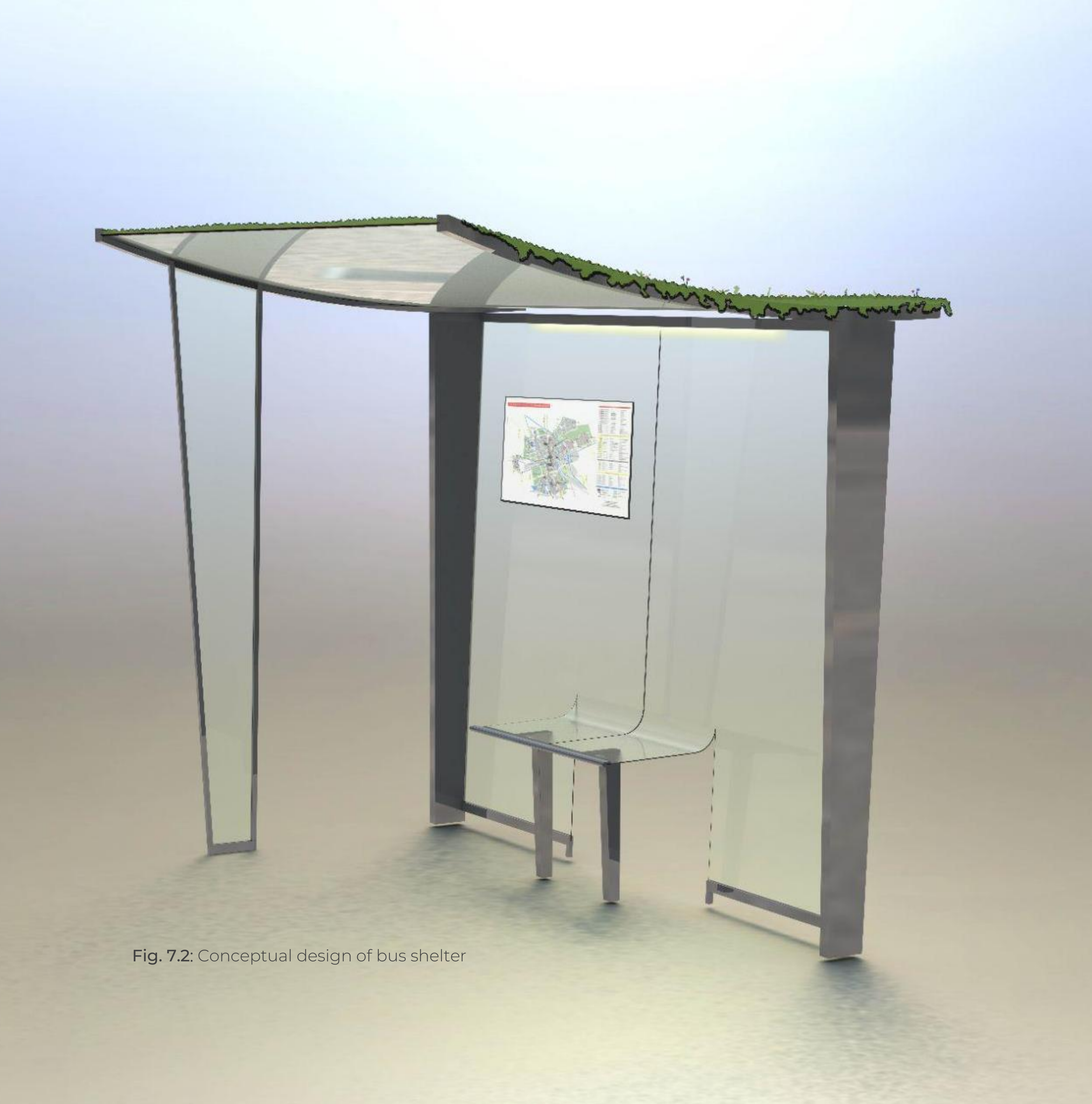
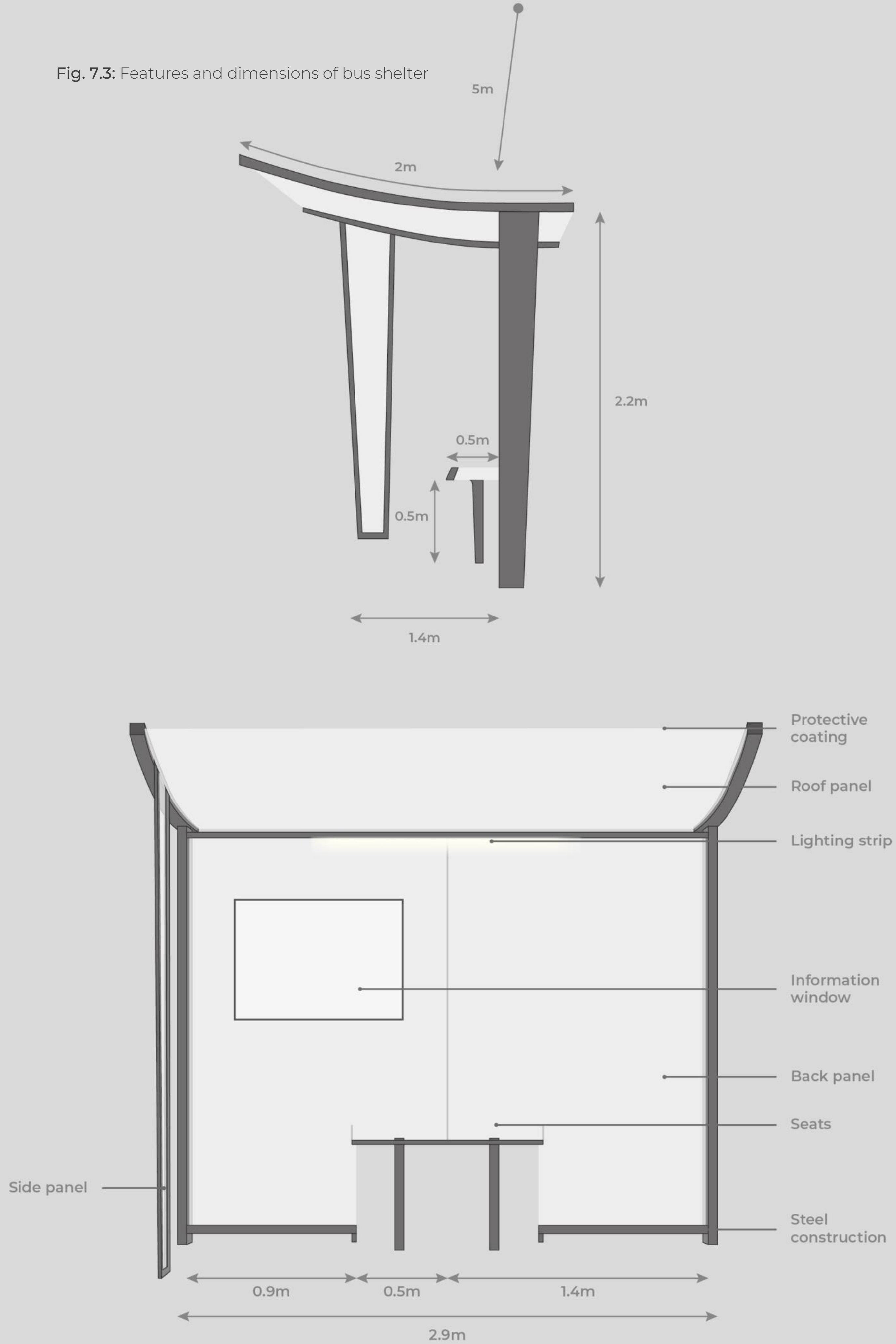


Fig. 7.2: Conceptual design of bus shelter

Fig. 7.3: Features and dimensions of bus shelter



The bus shelter has an anthracite-coloured steel construction that encloses the laminate panels. The back wall of the bus shelter is made out of two separate laminate panels. The laminates stay in place and in the right shape through form fitting by a steel u profiled rails along the sides. This method of assembly eliminates the need of fastening holes in the laminates, preserving the material's qualities. It also helps in protecting the exposed edges of the laminate against environmental influences. Seating places have been formed by bending the vertical back wall to a horizontal position with a radius of 100mm. This also highlights the flexibility of the material. Two beams add support to the seating places. A side panel is added for aesthetic purposes and to add a feeling of cover. A bus stop sign could potentially be attached here to add more recognisability. An information display has been placed on the left back panel, allowing for free space to inspect it up close. The roofs are planted with sedum, a kind of succulent plant that can withstand almost all weather conditions. When placed in the context of use, greenery can be planted against the back.

7.4.1 From wind turbine blade element to bus shelter panel

Figure 7.4 gives a visualisation of how the bus shelter is constructed from the laminates of the wind turbine blade sections. The elements are cut from the section, delaminated and then bent to the desired shape at which it is locked in shape by the steel frame. Because, as discussed in chapter 5.1, the laminates are the stiffest and strongest in the direction of the fibres, the laminates have been used so that the 0° is oriented along the length of the panels, optimal for the design (see figure 7.4). As concluded from chapter 5.2, this way of bending also goes easier than in the perpendicular direction. Additionally, the curvature in the roof increases the moment of inertia, making it more stiff and minimising the chances of buckling.

The design of the bus shelter makes use of the inner laminate of the sandwich panels retrieved from the inboard section. Besides the fact that the inside delaminates more easily, contrary to the outside laminate it also has a consistent laminate thickness. For this project it was decided not to further pursue the possible uses and opportunities of the outside laminate.

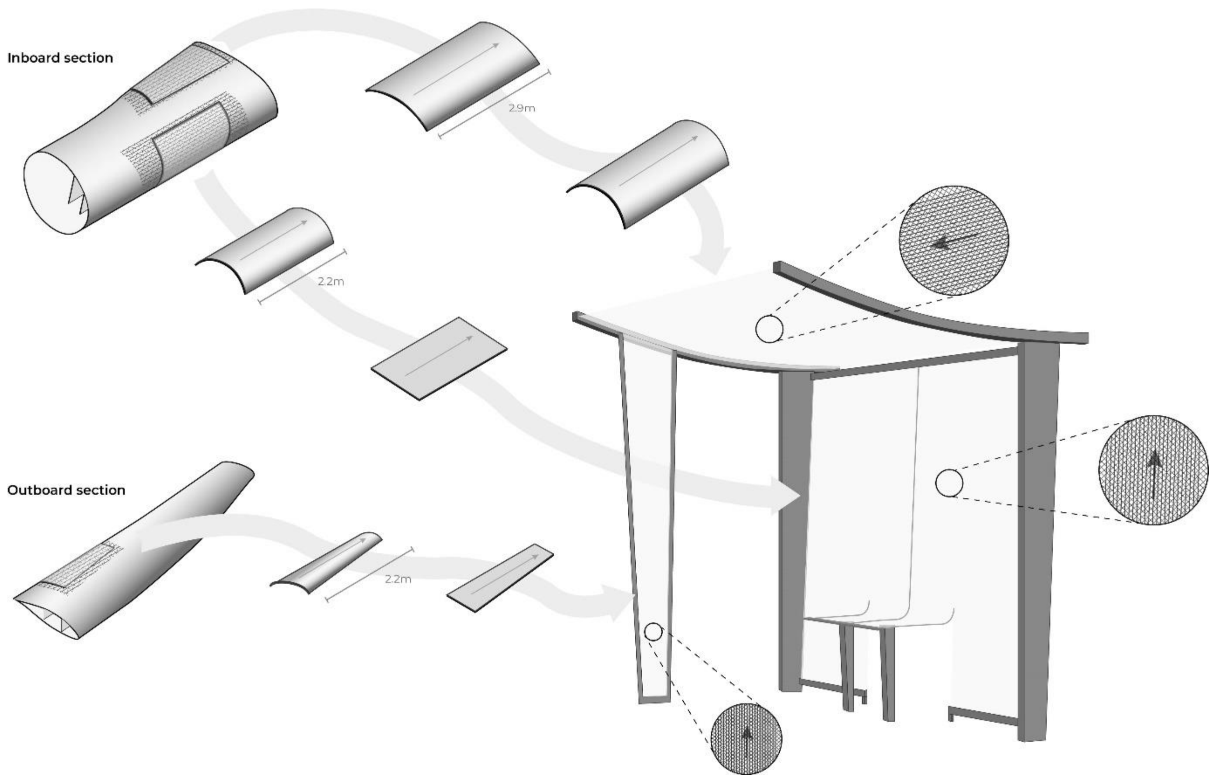


Fig. 7.4: Origin and fibre orientation of laminates used in the design.

7.4.2 Environmental conditions

Coating

As described in chapter 4.4 a coating needs to be applied to the edges of the laminates as protection against environmental influences such as moist or bacteria. However, concluding from the material properties, also the requirement of ensuring that the laminates used in the design are not flammable was derived. To improve the flame resistance of laminates and meet this requirement either flame retardants could be incorporated in the matrix and/or reinforcing fibres during manufacturing, something which more and more companies develop (*SAERTEX LEO® Serie, n.d.*), or a protective coating can be added to the laminate. The first is not an option as current wind turbine blades entering the end of their life do not (yet) contain this. Therefore, a coating is applied, an example of which is a poly(vinyl alcohol) (PVA)-based coating which has been proven to adhere well to laminates (*Floch et al., 2020*). The coating can be colourless or mixed with the paint.

Having said that, it is important to evaluate the environmental impact of the possible different coatings and make considerate decisions, also about the extent to which it complicates the retrieval of pure materials at the end of life.

Wind forces

Quick calculations were conducted to check whether the design complies with requirement 1.3 and can withstand harsh weather conditions. The steel frame is left out of scope for this calculation as it is assumed to be able to resist these forces and is not the focus of this project.

Harsh weather has been defined as maximum wind forces. The maximum wind force is 12 on a Beaufort scale, equalling to wind velocities greater than 32,6 m/s (*KNMI, n.d.*). The forces acting on the bus shelter because of these high wind speeds are the drag forces and are assumed to be most critical on the back panels of the bus shelter as these have the highest surface area and are oriented perpendicular to the wind, assuming the wind predominantly moves in horizontal direction.

The drag force can be calculated using the formula $F_{drag} = C_d \cdot A \cdot \frac{\rho \cdot V^2}{2}$ in which

C_d = 1.28 (Benson, n.d.)
A = 2.2m · 1.4m = 3.08 m^2
ρ = 1.225 kg / m^3 at 15 ° C
V = 32.6 m/s

This gives a force acting on one back panel of 1670 N, equal to 542 Pa which is below the flexural strength. This would be the force applied on the entire panel. However, even if the 1670N would be applied at one point in the middle of the laminate, the laminate would still not fail. If we simplify it as a three-point test and we apply the formula for calculating the flexural strength $\sigma = \frac{3 \cdot F \cdot L}{2 \cdot w \cdot d^2}$ with

F = maximum force applied	= 1670 N
L = length of the element	= 2.1m
w = width of the element	= 1.4m
d = thickness of the element	= 0.003m

We get a maximum stress of 417.5MPa, still a safety factor of 3 below the flexural strength of 1.3GPa. With the amount of stress the laminate material can withstand before it yields, also known as the flexural strength, being 1.3 GPa, the laminate will not break and is well able to withstand the high wind velocities.

Vandalism

Building on the calculations made in the previous section it shows the laminates are able to withstand high impact forces. These can be from wind but also from vandalism-like activities. Glass fibre reinforced polymers are less stiff than glass but stronger and able to elongate more (*Ansys GRANTA EduPack, 2022*). In other words, GFRP are less brittle than glass and are able to absorb more energy. The material is therefore potentially better in resisting force impact type vandalism. Furthermore, based on findings from the bending tests, illustrating the way the material breaks, in case the laminate does break, it does not result in material scattering everywhere as the fibres keep the material together.

Additionally, strategically planting greenery in the form of shrubs and bushes around the back of the bus shelter can make it more difficult for vandals to reach the bus shelter, at least from one side, and can discourage vandals who prefer less well cared for properties. Also, the presence of light in the bus shelter takes away the cover of darkness and therefore has an additional function of deterring vandalism.

However, these are mostly theorised functionalities. Application in practice is needed to verify or disprove these thoughts and iterate towards potentially better approaches.

7.4.3 Storytelling the origin of material

Besides providing shelter, the design has the function to create awareness and appeal to the imagination of the viewer. To achieve this, the design and its background story need to be understood by the public. Currently, the fact that the bus shelter reuses and wind turbine blade material in order to preserve and exploit its value is not directly clear by looking at it. For this reason, a story telling aspect has been added to the design.

The right balance between completeness of the story, the understandability and aesthetics needs to be found. To aid this process a target group to address with the story telling has been defined. Based on who most would most commonly encounter the bus shelter and the desire to convey the story to a broad audience, this was determined to be Joe Public. Therefore, it was chosen to keep it simple and focus on showcasing the origin of the material only, thereby leaving the fact that the laminate originates from the inboard section, that it has been delaminated and that this has allowed for reshaping them to form a bus shelter, out of the story to be communicated. Simplicity is key here.

Still, then there are many ways to go about this. Options that have been considered are amongst other visualising large, abstracted turbine blades coming from the upper right corner of the back panel, a patterned strip, a label in the corner or making it completely white as this is the colour of wind turbine blades. In the end, a line drawing of a wind turbine, the origin of the material, stemming from a continuous horizontal line together with a catchy slogan has been chosen. The motto for this was less is more so that it can be understood at a glance. This way, it is more likely that, for example, also passengers in the bus passing by will be able to see it. The height has been chosen for it to be readable and accessible for everyone.

Fig. 7.5: Intended visualisation of storytelling on the bus shelter.

7.4.4 Recognisability

One of the requirements set is that the bus shelter must exude recognisability, clarity and safety, all of which are subjective aspects. To evaluate whether this requirement has been met, a number (10+) of casual conversations were held with people that are considered as the general public, differing in educational level, age and background. Without providing prior knowledge, they were shown a render of the design and asked what they thought the function of the design was (recognisability), if there were things they did not understand about the design (clarity) and what their opinions on safety regarding the design were.

With the exception of one person guessing the design was for a tram stop and one person guessing it was an outdoor smoking area, the large majority believed it was a bus shelter. During manufacturing of the demonstrator also many people that walked by believed it was a bus shelter. From this it is concluded that the design is recognisable as a bus shelter. Additionally, when placed in the context of use and the presence of a bus stop sign, it is assumed that it will only become clearer that it is a bus shelter.

Regarding clarity, everything was lucid for the majority. Two people commented on the seat being a bit hard to understand and the same goes for the greenery on the roof. However, through further questioning this has been ascribed to unclarity in the render and for that reason not considered an issue for the actual bus shelter.

Lastly, also the influence of the bus shelter on the perception of safety has been established as good, and in comparison, better than current standard bus shelters. The design was considered attractive but more importantly, predictable and easy to oversee. According to the interviewees, although it might be less desirable in terms of wind, the open sides of the design added to this feeling as it does not give a feeling of being enclosed and the user has an unobstructed view towards both directions, but also the bus driver is able to see the user better. Also, similar to the argumentation for deterring vandalism, the presence of light added to the feeling of safety too.

7.5 Conclusion

The design of the bus shelter is an example of how laminate material from a wind turbine blade can be reused. A list of requirements and wishes was set up to evaluate the bus shelter and come up with the most satisfactory design. The design is simplistic, consists of only a few different parts and without elements that need to be tailor made for each separate design. This makes the design suitable for wide scale manufacturing. In the previous chapter some other aspects of the design have been elaborated. It is concluded that the bus shelter complies with the requirement and wishes.

Also, some challenges were addressed namely the need of locking the laminates in shape and the risk of vandalism. The first has been addressed by guiding rails on the sides of the laminates that prevent the laminate from returning to its original shape. The second has been thought about and well considered. However, it is recommended to verify the theories in practice.

8. Demonstrator

A conceptual prototype is made to evaluate the research findings, check their applicability on a larger scale than tested and demonstrate the potential possibilities. The focus is put on examining the ability to bend the material, maintaining the desired shape of the material and evaluating the strength and stiffness of the material. Things that are left out of scope are the electronics, coating, greenery and steel frame of the bus shelter as these do not touch upon the core of the project or have proven to be feasible. Because the material properties such as the strength and bendability in relation to the size and thickness of the material are not easily scalable, it was decided to build the demonstrator true to size. Though, because for the purpose of the demonstrator it is not necessary to build the entire design and due to limited time, space and budget it was decided to only build the right half of the bus shelter.

8.1 Realisation

Some adaptations to the final design presented in chapter 7 have been made. Because of the proven strength of steel, a reduction in weight and easier manufacturability it was decided to build the frame from wood. This means wooden guiding rails as well as a wooden pillar. This pillar is built up out of veneered smaller wooden beams. Furthermore, the demonstrator was designed to be demountable and transportable and is therefore put together with screws. Also, for the demonstrator the seat has been drilled onto its support, in the envisioned design this too can be done through form fitting.

As only half of the bus shelter is built, a side wall with a reflective surface is added to mirror the half and make it appear as a complete bus shelter. This side wall is also used as support to mount amongst other the seat support and guiding rails to and provide balance for the demonstrator to stay upright as the frame of the bus shelter cannot be mounted into the ground.

Fig. 8.1: Construction of wooden framework for demonstrator

8.1.1 Laminate

Despite efforts, attempts to obtain wind turbine blade material in the size and quantity usable for the design turned out unsuccessful. Therefore, it was decided to simulate the material and manufacture laminates in a way so that they turn out as realistic and representable for wind turbine blade material. This chapter describes the choices made for the manufacturing of the laminates.

Concluding from research it was determined that the laminate material is made up out of 3 layers of triaxial glass fibre material with a total thickness of 3mm. In the NREL offshore 5MW wind turbine concept model the triaxial lay-up is notated as $[\pm45]_2[0]_2$ (*Resor, 2013; Griffith & Ashwill, 2011*). This stacking sequence has been understood as the following asymmetric order of plies: +45°,-45°,+45°,-45°,0°,0°. However, since in practice laminates are usually stacked symmetrically (*Jansen, 2018*) it was decided to construct the simulated laminate symmetrically with the order of plies being +45°/-45°/0°.

Biaxial material was made available by Julie Teuwen, it was therefore determined to construct the triaxial layup out of biaxial plus UD glass fibre material. The exact behaviour of the material when constructing it like this versus true triaxial material in which the fibres in all different orientations are all stitched together, differs (*Julie Teuwen, personal communication, 22 March 2023*). However, as the reference blade does not go into detail about this type of information and the exact influence of the stitching is not set as a boundary for the project, a layup consisting out of biaxial plus UD glass fibre material is deemed sufficient for the purpose of the demonstrator.

Table 8.1: Building blocks for triaxial material.

Name	Fibre material	Fibre orientation	Weight
Biax	Glass	+45°/-45°	820 [g/m^2]
UD	Glass	0°	400 [g/m^2]

The exact weight per square metre of the triaxial material from the reference blade is not mentioned. Through making a test laminate it was concluded that one simulated triaxial layer would have a thickness of approximately 1.3mm. This differs from the layer thickness (0.94mm) in the reference blade. making it hard to have both the total thickness of the laminate and the number of layers correspond with the reference blade. Yet, the thickness is assumed to be a relevant parameter when testing the deformability of the material because of its exponential influence on the moment of inertia. This, plus the fact that even though the number of layers is not the same, with similar thickness and a similar fibre to matrix ratio, the total volume of the fibre will be the same, it was decided to go with two layers of biaxial to get as close as possible to the thickness that was concluded from the research.

From the weight distribution of the fibre orientations in table 8.1 it can be seen that the simulated laminate has its weight rather equally distributed over the +45/-45/0 directions. 400 g/m^2 UD was chosen based on availability. It is possible that in the wind turbine blade there is a focus on UD and for that reason there is more UD compared to +45/-45 orientations. Though, this was undisclosed in the reference blade. Hence, equal distribution of the fibres was deemed sufficient for the purpose of the demonstrator.

The width of the biaxial and UD glass fibre material is 1.35m and 1.25m respectively. Therefore, to acquire the desired width of the laminates, two parallel strips were used with an overlap of 0.2m.

In the reference blade the matrix material is not specified beyond epoxy resin. Based on availability and costs, for the simulated laminate Hexion RIM135 injection epoxy resin is used. This resin is certified by Germanischer Lloyd for yacht building and wind turbine blades (*PolyesterShoppen BV, n.d.*).

The laminates are made so that they are curved, like laminates retrieved from wind turbine blades. Because of practicalities, both laminates are made to have the same amount of curvature: a radius of 7.5m. The amount of curvature is decided based on the curvature of the panels of which, due to size, the material for the bus shelter most likely originates from, namely the trailing edge of the inboard section. This also present the opportunity to test both bending and flattening of the laminate for the construction of the bus shelter. Namely, with a radius of 7.5m, it needs to be bent to a radius of 5m for the roofing and to be flattened for the back panel.

8.2 Production process

As can be seen in figure 7.3 the demonstrator is built up out of 8 parts: the back panel laminate, the roof laminate, the pillar, two guiding rails for the back panel, one guiding rail for the roof panel, the seat support and the side wall. As the wooden parts are constructed through rather straightforward woodworking processes, laser cutting and foam cutting, it is most interesting to look at the production of the laminates.

The laminate is made using a similar manufacturing method as used in the production of wind turbine blades and described in chapter 2.3, namely using resin infusion technology. This process is explained using pictures, see 8.4. A schematic of the final set up is visualised in figure 8.2.

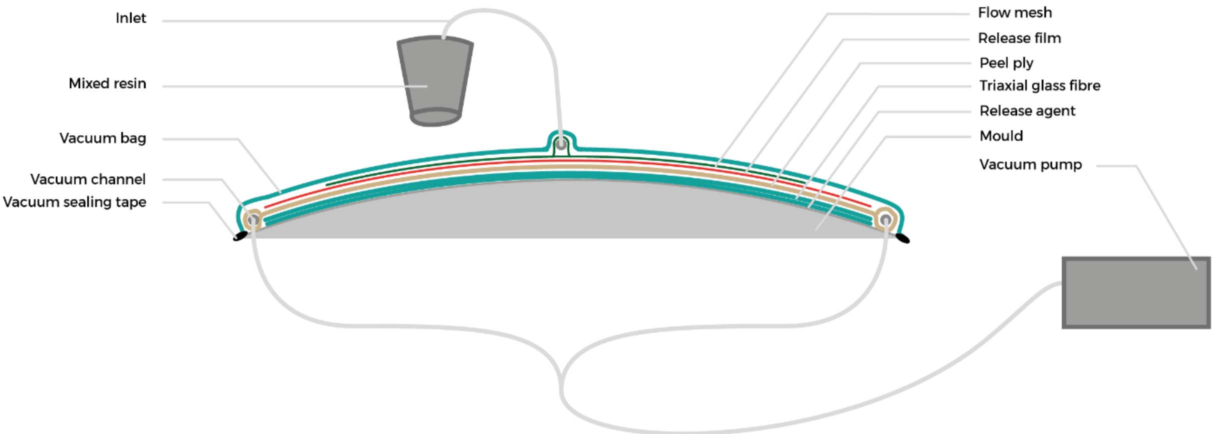


Fig. 8.2: Schematic of the manufacturing set up.

A mould for the infusion process was constructed out of 3 plates of aluminium (maximum dimension available were 2m x 1m), taped together to form one aluminium plate with dimensions 2m x 2.3m. There is a small seam between the plates as they did not fit together perfectly. The aluminium plate rests on laser cutted wooden bulkheads to create the right curvature.

Fig. 8.3: Bulkhead supporting the shape of the mould.

Fig. 8.4: Production process of the laminates

Description:
From top left to bottom right: Coating the mould with release agent to ensure that it will detach from the mould, laying the glass fibres and constructing the triaxial layup, laying the peel ply, laying the release film, laying the flow mesh, constructing the in- and outlet tubes, building the vacuum bag, creating the curvature in the mould, preparing the epoxy by mixing it with hardener, infusing the fibres through vacuum and lastly, removing the manufacturing consumables.

After removing the manufacturing consumables, the laminates were cut to the right size. The results were two curved laminates, one for the back panel (2.1m x 1.4m) and one for the roof (1.85m x 1.47m).

8.2.1 Conclusion and discussion

Producing the material and having it in your hands really contributes to getting a feel of the material and making conclusions. This sub chapter present the abnormalities and insights gained during the manufacturing process and reflects on the aims for the demonstrator.

Laminate quality

The final thickness of the laminate for the demonstrator amounts to approximately 2.5mm for the most part and 3mm at the parts with overlap, which is clearly visible in end product. Moreover, the laminate contains material defects in the form of dry spots, the seam between the two aluminium plates is visible and tangible and the laminate has some aesthetic flaws like spots where the peel ply tore and manufacturing smudges. In other words, the laminates are not perfect. Though, it can be argued that laminates retrieved from wind turbine blades after 25 years of use, plus potential another reuse application, are likely not in the best condition anymore too.

Fig 8.5: Darker strip showing the overlap

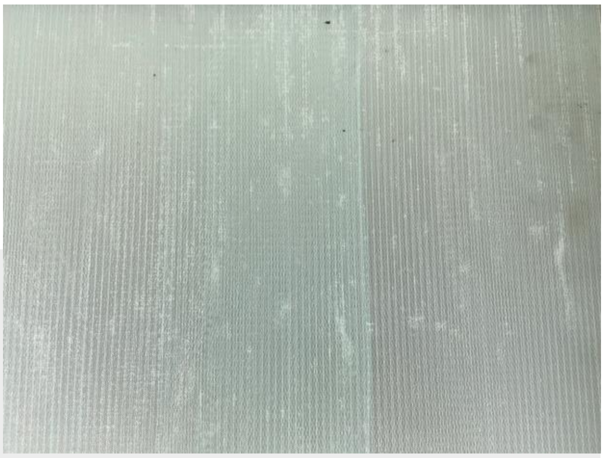


Fig 8.6: Dry spots.

Fig 8.7: Spot missing peel ply and smudges

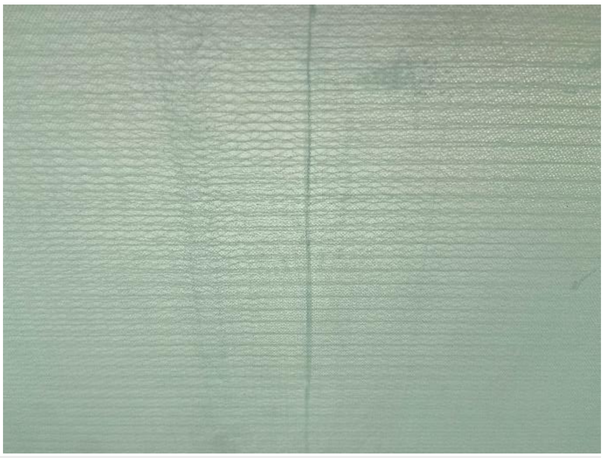


Fig 8.8: Visibility of the seam

The material properties of the laminate have not been scientifically tested. Though, they were relatively heavy (approximately 12.5kg) and appeared to have sufficient strength. Quick tests performed with smaller pieces of the simulated material revealed that the laminates could be bend to a similar degree as tested with real wind turbine blade material. The stiffness will be elaborated in the next sub chapter.

Stiffness

The laminate panels were less stiff than anticipated. The curvature of the laminates disappeared as the curvature of the mould was removed; the laminates sag under their own weight. As a result, due to the lack of stiffness, it was no problem to adjust the shape of the laminates for them to fit as the back panel and the roof of the bus shelter. The flexibility even allowed for further bending.

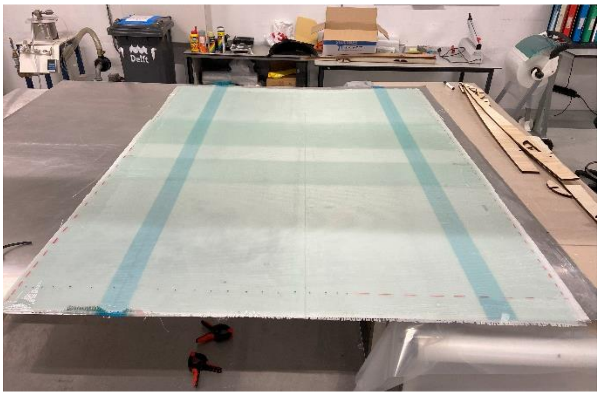


Fig. 8.9: flattening of the laminate without applying external force.

Simultaneously, as a consequence the roof buckled. An adaptation to the design in the form of extra external stiffness was necessary to counter this. This has been done through applying a rigidly made U-profile on both ends.

Fig. 8.10: The roof without (buckling) and with the rails

Handling these panels has given an insight about the stiffness, relevant for the development of reuse applications. However, a point of discussion is the representativeness of the simulated laminates. The difference in the laminate thickness or the exact matrix material might give the simulated laminate different material properties, resulting in a stiffness that is not matching. Test have exclusively been performed with smaller samples, testing with larger would have to confirm or deny the findings. Though, smaller pieces of the simulated laminate act stiffer and behave similar to the samples from wind turbine blades. Therefore, the apparent reduced stiffness might also simply be a consequence of the large size of the laminate, and also be the case for wind turbine blade material.

Maintaining the desired shape

The roof and back panel formed no problem maintaining their desired shape because as indicated, the laminates lacked stiffness. More difficulty arose when the seat needed to be bend into its position. This was attainable but an increase in internal stresses could be observed as the laminate started to distort. Further deformation of the material was limited by the strength of the framework and the absence of more guiding structures. The desired bending radius of 100mm has thus not been met. It can be concluded that to combat distortion of the material due to high elastic stresses, the laminate needs to be more secured. In the envisioned design of the bus shelter the strength of the framework is believed not to be a problem as this is a steel structure.

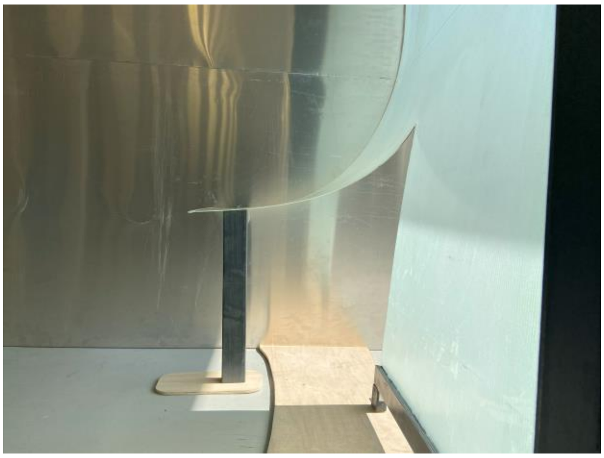


Fig. 8.11: Side view of seat curvature.

Fig. 8.12: Distortion in the back panel.

Assembly

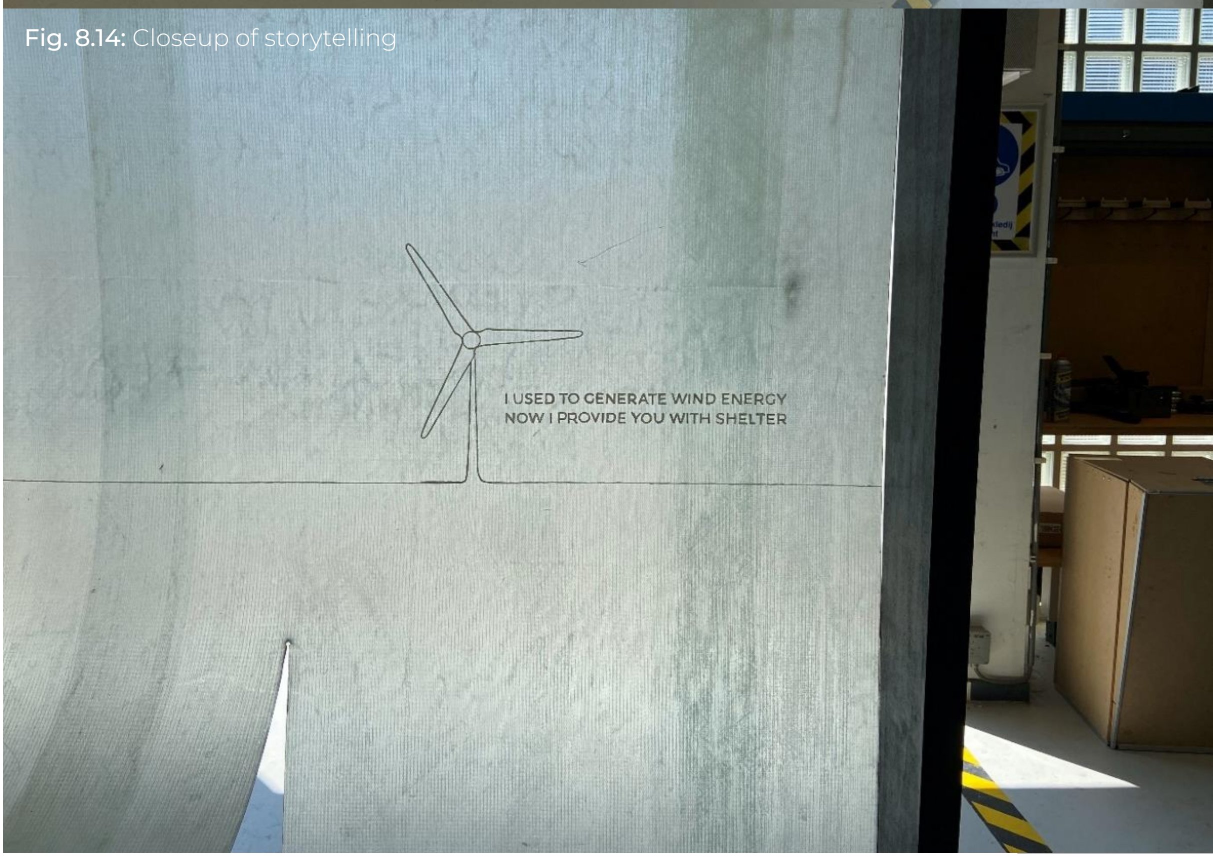
Two extra plates for foundation were added to compensate for the fact that the demonstrator is not mounted into the ground and the laminates, and the partly assembled components, were heavier and bulkier than expected making assembly a three men's job. Other than that, the assembly went as expected, the techniques work and the seat is capable of holding (at least) one person.

8.3 Result

Putting it all together, including the storytelling aspect, gives the following results. Applying the reflectiveness to the aluminium has not been achieved before the deadline of the report.

Fig. 8.13: The demonstrator

Fig. 8.14: Closeup of storytelling



9. Innovation

The proposed design for a bus shelter, built from laminates retrieved from decommissioned wind turbine blades, is the result of a project exploring ways to be able to preserve the value of the material by reusing it on a large scale. This chapter dives deeper into the question whether the project and its outcome, both in terms of insights and the final design, can be realised, whether it addresses needs, and if it would be able to survive in the long term.

9.1 Feasible

In essence, the demonstrator shows the feasibility of the project outcomes. Although the result of the project may sound disputable at first: being able to reuse curved and unconventionally shaped sandwich material from wind turbine blades in a diverse and scalable way, delaminating the material has granted the introduction of new design freedom, necessary to achieve potential large-scale applicability of the material.

Through testing the project has demonstrated that delamination of composite sandwich panels is attainable, and it has discussed methods for achieving similar results in the industry. Experiments and the use of the material in the demonstrator have shown the added design freedom as a result of this delamination: being able to rather extensively shape the laminates. Some first pit falls for designing with the material have already been encountered through making the demonstrator. This, together with a thorough understanding of the material can be used to ideate and find reuse applications, suitable with the characteristics of the material.

Following this approach, the floor opens for the development of more designs and that way preserve the value embedded in the decommissioned wind turbine blades.

9.2 Desirable

Although perhaps not for individual users specifically, but as discussed in chapter 1. Introduction, the project and its outcome does address clear needs of society. Namely, the need to stop the decommissioned wind turbine blades turning into waste.

The project functions as a means to do so and instead reuse the material. With governmental bodies and the public already increasingly embracing this need for sustainability (*Deloitte, 2022*; *European Parliament, 2021*), a design, such as the bus shelter, also follows their values. Nevertheless, it has the potential to add new value to several different stakeholders too. For the owners of the wind turbines, the material is now considered waste and costs money to remove after the initial use phase. However, recognising the possibilities, it could be given a new meaning and be considered a valuable and potentially profitable resource. Similarly, what the project has shown can be of value to designers and function as a tool and a stimulus in their design process. However, these are hypothesised benefits of the project and the bus shelter. Future research is recommended to dive deeper into the stakeholders' potential attitudes and responses to the concept idea.

Lastly, the approach presented in the project is of value to the circular economy. Large scale reuse of the material is facilitated and through the reuse application, the qualities of the material are exploited. This way the integrity is preserved and the need for new, virgin and potentially expensive material can possibly be reduced.

9.3 Viability

The difficulty of recycling wind turbine blade material is fought on two sides: researching how the material from the blade can be reused and researching what different and easier to be recycled material for the blade can be made. When both are successful this means that it is likely that the inflow of thermoset material and the obstacles it brings will ultimately stop. This would be good news but does not change the fact that although it can achieve circularity, also for thermoplastic materials it is valuable to preserve the integrity of the material for as long as possible. This way the loop is kept narrow, in accordance with the circular economy principles. And, Karel Brans (*2023)* has shown that also with the use of thermoplastic material in wind turbine blades, delamination still presents opportunities for reuse.

Thus, the methods used, delamination and reshaping, are likely to remain relevant in order to achieve appropriate reuse applications, of which the bus shelter is an example. The question whether this method will be able to survive on a longer term will most likely be a matter of profitability. Future work researching the monetary matters connected to this is recommended as this has not been the focus of this project. One important condition to allow for the profitably of reusing decommissioned wind turbine blades has been satisfied: enabling large and diverse scale usage.

10. Discussion

Nearing the end of the project it is appropriate to evaluate, discuss the results and asses potential implications and limitations. This is done in triplicate, namely the design process, the research outcomes and the demonstrator.

Design process

Starting with the design process. After having recognised the knowledge gap and identified the approach the project was tackled in a straightforward way. E.g., before researching the deformation possibilities of a detached laminate, first the feasibility of actually separating the laminate from the core material needs to be investigated. Nevertheless, in the continuation of the project the research attention regularly shifted back and forth because of the outcomes. However, a more iterative approach and determining an exemplary reuse application at an earlier stage would have allowed for an even more focussed research approach.

The project has an explorative approach, looking into an hypothesis set at the beginning. The waters of the many aspects involved in this are inspected, showcasing the line of thought and its potential. Despite the personal tendency to often go too much into detail and preference to quantify and concretise, the rather superficial though broad insights can function as a starting point for future research.

The ideation method used is structured, starting broad and stepwise narrowing down to what was determined as the most suitable reuse application. Nevertheless, some of these steps rely on quantification of the decision criteria in some sort although they are not always objectively quantifiable. As a result, the outcomes might differ for different people due to different reasoning or understanding. Yet, it is a way to explore the potential of the material in a variety of markets in an organised way. It's the designers' job to add nuance and interpret the results effectively.

Research outcomes

As stated above, the project was mainly explorative. This also means that many things need to be investigated further to obtain quantifiable data.

A lot of conclusions have been made primarily based on the reference blade and the test material. It has been acknowledged that there is great variety in the design of wind turbine blades. Additionally, the design, materials used, and manufacturing techniques are continuously developing. Therefore, exact applicability of the findings on the material at hand may differ.

A limitation to the research has been the limited number of variables, an important of which is the exploration of curved wind turbine parts. The focus of this study was primarily on curved elements, though the test have been performed with flat specimen. Furthermore, during the project, curvature and bending has been somewhat simplified to single curvature but wind turbine blades have a rather organic shape containing parts with double curvature. It has been assumed that the delamination and bending of these elements is for a large part comparable, but further research should establish to what extent this is true. One implication imagined is that the curvature of a panel might hinder the use of some delamination methods.

Another example is the laminate thickness, which was determined to be 3mm. A thicker or thinner laminate has a different stiffness, potentially having an influence on the delamination and the suitability of the reuse application. Similarly, the thickness of the core material can potentially have an influence on the ease of delamination as well as it may be less rigid or more difficult to grip. Therefore, although the thickness of the laminate or core material might have little to no direct effect on the adhesion between the two, it might influence the ease of delamination. Saseendran et al. (*2017*) too acknowledge this.

For this reason, the influence of more variables regarding the element properties and their effect on the research outcomes need to be investigated. However, the project has demonstrated the general potential which can function as an incentive for wind turbine manufacturers to carefully consider design choices for future blades.

Although thought has been given not to abolish the core material, the reuse of the core material has not been included in the scope of the project. Naturally, this should also be handled in a sustainable fashion.

Demonstrator

The common thread running through the project was the scalable applicability of the material. A bus shelter is such a design that is present in large numbers in the streetscape. However, the use of the material is not limited to bus shelters. The approach taken delivers a material with considerably good qualities, and that allows for some degree of shaping, making it suitable for a broad range of applications. Although the use of the material in different areas need more exploration, the conclusion can be drawn that through the approach a large quantity of end-of-life wind turbine blade material can be reused.

The aim of the reuse application and its design specifically was to simultaneously exploit and exhibit the material qualities and possibilities, as well as appealing to the imagination of the viewer. This is also how it has been expressed in the design vision. The bus shelter has been intentionally designed to utilize the qualities of the material, which is described in chapter 7. Whether it also exhibits this as well as appealing to the imagination is a more subjective matter. This has been evaluated through personal judgement as well as discussions with people around. Most people were immediately captivated by the large size of the demonstrator, showed interest in the laminate and saw the practicality of the material. Nevertheless, this has not been quantitively assessed with a large group of people.

Upon designing there was the fear of turning the bus shelter too much into an art installation and giving it the appearance of being one of a kind instead of large scale. Yet, in hindsight the final design of the bus shelter could have contained more curvature and bended elements to put more emphasis on the freedom and possibilities of the material. Additionally, there could have been a deeper dive into the aesthetics. It was chosen to keep the natural appearance of the material, also because the exact condition of the original paint and coating is unknown, as discussed in chapter 4.4. However, there is room to play with the looks of these panels, possibly combining this with a coating. Though, the details should be carefully considered based on the intended goal. For example, use of the colour white may add to the recognisability as blade material, a decorative design may raise more awareness or appeal more to the imagination, but a plain look may illustrate the potential for wide scale applicability of the material better. For this reason it is good to have the intention clear.

Lastly, regarding the embodiment of the demonstrator. It is a limitation that no real wind turbine blade material has been used. The laminates used have been simulated according to real wind turbine blade material in the best way possible but it is interesting to look how real material would differ from simulated material. Also, the construction of the physical demonstrator could have benefited from a more profound framework. The possibility of showcasing the achievable bending and shape adjustment of the material was limited by the strength and stiffness of the wooden frame. Nevertheless, by using steel that has been sunk into the ground, as envisioned for the design, this is believed to not be a problem.

The demonstrator has been made demountable and allowing for reuse of all materials involved. However, little can be said about the life span and status of the material after its lifespan. Deploying the bus shelter would give more information on this as well as show any unforeseen aspects and potential implications.

Debate

Throughout the project the debate about scalable solutions and preservation of material integrity frequently arose. As pointed out earlier, splitting the material enlarges the choice of possible reuse applications but at the same time diminishes the material integrity. This can also be related back to the circular economy frameworks. Often it is the bigger the circular loop of a product and thus the closer you get to the individual resources, the more and wider applications that are possible, but the less of the product or material integrity is preserved. On top of that, naturally, the goal of preserving the material integrity comes with the need of little to no extra energy, time and effort. With respect to delamination and facilitating large scale applicability of the material this is different. This is a deliberate trade off you must make.

An answer to this is exploring more options in which more of the material integrity can be preserved, with the result of probably having to deal with the curved and unconventionally shaped elements as is. The extent to what that hinders broad scale applicability needs looking into. Free form architecture may be such an application. Simultaneously, the process of delamination needs to be developed for it to be done quick, easy and in an efficient manner and this way fight the battle against the waste on two fronts.

11. Conclusions

In this study, delamination of sandwich structured composites and the added design freedom as result of that is presented as an approach to facilitate reuse of wind turbine blade material in a diverse range of applications and in a scalable practice. The project started of with identifying the context, its knowledge gaps and forming an design assignment. This revolved around the following formulated research questions:

What section(s) of the wind turbine blade is the focus of this project?
It was found that the 45 wt% of a wind turbine blade still in need of a well-defined structural reuse solution was mainly located in the cylindrically shaped inboard and air foil shaped outboard section of the blade. The material in question is a sandwich structured composite material with glass fibre reinforcement and either a polyester, but most probably, a polyester matrix material. The core material is either Balsa wood or PVC or PET foam.

What are the characteristics of the elements retrieved?
The segmentation patterns are confined by the spar caps and edges. Nevertheless, this still allows for the retrieval of relatively large sandwich panels in both the inboard section and outboard section. These elements contain different amounts of curvature, ranging from strongly curved to near flat. The laminates mainly consist out of triaxial fibreglass with a thickness of 3mm and possess great material qualities, the most outstanding being its strength, stiffness, light weight and excellent durability in most atmospheres.

How can the laminates of the sandwich structure be separated from the core material?
Testing demonstrated the feasibility of delaminating a sandwich panel. It moreover revealed that the result of the delamination process and the type of failure is depended on the sandwich structure's core material, but it has been acknowledged that more in depth research, investigating a greater variety in variables needs to be conducted. Based on results and practicality, a climbing drum peel method, exploiting the low peel stress resistance of the sandwich panels is determined to be the most promising for retrieval of laminates.

To what extent can the shape of the laminates be altered after delamination?
The laminates are capable of elastically deforming and allowing for altering of the shape. The minimum bending radius for the reuse application was determined as 100mm. Tensile tests revealed that the bending of the laminates did not significantly material properties. Also, the flexural properties are orientation dependent as bending in the orientation parallel to the fibres requires more force.

What scalable reuse application for wind turbine blades has the most potential?
Based on the identified qualities of the material and sustainability considerations, the urban furniture market was one of the markets qualified as more relevant and potentially best at exploiting the material properties of the blade elements. The remaining ideas were then ranked on what was deemed important for the project: preserving the material integrity as much as possible and mass scale application of the material. Through formulating a vision, in the end a bus shelter was determined as the most suitable application for the material.
The creation and manufacturing of a design for the bus shelter gave new insights into the use of the material. It was found that, in large sheets, the material is less stiff than anticipated. Nevertheless, this is easy to resolve.

To conclude, an application for the reuse of composite materials from wind turbine blades on an industrial scale has been designed. This application stems from a systematic approach that can facilitate this, namely the delamination of the composite material and consequently reshaping it.

Research in this has provided insights into the identified knowledge gaps and can be of relevance for all stakeholders involved.

12. Recommendations

A few recommendations stem from the project, not only in direct relation to the scope of the project but also with regards to the wind industry in general.

One of the first things a designer wanting to do something with the blade runs into is the lack of data on the material. As already briefly pointed out before, there is great variety amongst blade designs. More precise documentation and public accessibility to technical data of the wind turbine blades would be beneficial for reuse. By knowing the exact material properties, composition and geometry, reuse applications can be developed more efficiently and be ready for implementation at the appropriate time. Moreover, as discussed in appendix B, this also contributes to potential lifetime extension of the initial material use.

The outcome of the research showed the possibility of reuse and what is required to achieve this. Wind turbine blade manufacturers can incorporate this in the design to ease this process at the end of life. However, the process includes delamination, something that blade manufacturers understandably actively want to prevent from happening during the lifespan of the blade. Initiatives to counter this are therefore being developed (*InfraCore Company, 2021*) which is disadvantageous for the reuse method. A trade off needs to be made here. An answer to this might be looking into adhesives that can be "activated" and "stopped" on demand meaning that an external trigger can weaken the bonding, resulting in delamination. Marques et al., (2020) pointed out a similar thought and stated that complete debonding is not yet reachable, but that the adhesive can be weakened so that less force is required to separate the core from the laminate. This would facilitate the reuse method suggested in this project. On top of that, the possibility of manufacturing wind turbine blades with a specific fibre layup which is not necessarily for the initial application in the wind turbine but already implemented for the intended reuse application(s) afterwards.

Something to point out is the sustainability of the manufacturing of wind turbines itself. Through personal experience and literature, the resource intensiveness of this process was experienced. At the manufacturing stage, not only does currently approximately 10% of the composite result in waste (*Psomopoulos et al., 2019*), but also a significant amount of single use equipment is also used. Liu and Barlow (2017) claim that 45% of the mass of the wind turbine blade is further waste from manufacturing and service. Besides, a process that requires such safety measures during manufacturing does not appear very sustainable. Hence, although wind turbines are a clean technology during their operational lifetime, not considering the shedding of large amounts of microplastics because of wear (*Solberg et al., 2021*), they require a lot of energy and resources during manufacturing, maintenance and end of life.

As briefly mentioned earlier, this project has not focussed on the reuse of the core material. The potential of this material (balsa wood or foam) needs more investigation to assess the importance of preserving the core material during delamination. One idea that came along is to delaminate one side and one side only of the sandwich panel. The leftover sandwich panel, a laminate with core material attached to it, can then be bend to the desired shape after which the individual laminate is also bend to that desired shape. Fastening these back together would again create a sandwich structure, be it of lesser quality and with internal stresses. Still, this approach could potentially adjust the shape of thermoset sandwich structured elements.

Lastly, the challenges of composite material to which a potential solution has been presented does naturally not stop at wind turbine blades. Many more industries such as aviation and marine manufacturers make use of the material. The translatability of the approach to these industries needs more looking into because ultimately, in order for the planet to become truly sustainable, all waste streams need to be addressed.

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Images

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Figure 2.1: Wind turbine blades vergadering windpark in afwachting. (n.d.). Depositphotos. https://nl.depositphotos.com/14704553/stock-photo-wind-turbine-blades-awaiting-assembly.html

Figure 4.1: Gonçalves, F. A. M. M., Santos, M., Cernadas, M. T., & Alves, P. (2022, August). Influence of fillers on epoxy resins properties: a review. Research Gate. http://dx.doi.org/10.1007/s10853-022-07573-2

Appendices

A. Project brief

Re-using composite material from decommissioned wind turbine blades

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 20 - 02 - 2023 | 10 - 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 earth's climate is changing which has adverse consequences. This is a result of the emissions caused by the fossil-based systems of energy production and consumption. Therefore, a global shift towards green energy from renewable sources is required. Wind turbines offer a solution to convert the kinetic energy of the wind, a renewable energy source, into electrical energy without emissions while doing so. This greatly helps in trying to reduce the impacts of the global rising energy demand, and thus large wind turbine projects are being executed.

However, less attention is paid to possible secondary effects of this renewable energy production. The use of composite materials in the wind turbine blades provide many advantageous properties for the desired functionality. Nevertheless, current wind turbine blades are primarily made of composite materials such as fiberglass infused with a thermoset resin. Unlike thermoplastics, you cannot remelt and process thermosets and this presents a challenge at the end of its life as this makes it difficult to recycle. As a result thousands of tons of decommissioned wind turbine blades are expected to enter the market the coming years which, with little to no other options, are most likely to be disposed of through landfilling or incineration, both of which are undesirable from many perspectives.

Better end of life alternatives for composite materials are therefore needed. Although they are there, recycling methods with the goal of acquiring the virgin materials again, like pyrolysis and/or solvolysis, mostly still operate on a laboratory scale. Moreover, though it is eventually necessary to prevent the loss of the material as part of the circular economy, the process is unable to preserve the materials' quality, structural integrity and value. This is a shame as obtaining this material and its qualities requires great efforts. Therefore, it is interesting to look at how the life of the product and the value of the material can be extended first. Preferably this solution enables repurposing of the composite material of the decommissioned wind turbine blades while maintaining the structural integrity.

This is a matter that involves knowledge and stakeholders from the complete lifecycle of the material as the outcome can be of value to improve each and every step of that lifecycle. From wind turbine manufacturers, to companies using the turbines, to companies dealing with the end of life or possible lifetime extensions to companies using the repurposed material. Instead of the material being a waste and costing money to get rid of after the initial use phase, the wind turbine blades could be turned into profitable products as it is seen as a valuable resource for new products.

space available for images / figures on next page

introduction (continued): space for images

image / figure 1: Windturbines in operation generating green energy

image / figure 2: Windturbine blades ending up as landfill

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.

A promising way of re-using the wind turbine blades is through segmentation, often referred to as structural reuse. Cutting up the blade into elements suitable for a new purpose makes sure the qualities of the material are preserved and utilised again. However, it is important that these repurposing solutions match the industrial scale in which the wind turbine blades become available; it should not be a drop in the ocean.

Related to this, previous graduates and PhDs have already looked at obtaining standard elements (planks, beams) from the blades. These standard elements make a clear and broad application of the material possible. One of their conclusions was that based on certain curvature tolerances, approximately 55% of the blade is suitable for this.
This leaves 45% of the wind turbine blade still in need of a well-defined reuse solution. The specific application and the exact shape of the elements, however, greatly affect each other; one sets preconditions for the other. Both are currently unknown variables.

One method that might bring about new options for reusing the thermoset wind turbine blades is splitting the sandwich panels of which it is built up. However, the exact chances it brings is unclear. Moreover, it has not yet been well defined what it requires to split these sandwich panels; separate the face sheets from the core material. Investigating this can lead to valuable insights and shed light on the physical and material considerations for future blade design of both thermoset and thermoplastic blades, ultimately leading to a more circular blade design that will enable re-use.

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.

I will design an application(s) for the reuse of composite materials from wind turbine blades on an industrial scale, containing a particular defined shape(s) and cutting pattern(s) that facilitates this. Focus will be put on the curved elements of the blade and what possibilities the splitting of the sandwich panels enables.

For the assignment a few research questions need to be answered:
- What does it require to delaminate the sandwich panels?
- What is the condition of the material after splitting the sandwich panels?
- Does the splitting of the sandwich panel add (extra) functionality or value to the material?

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 20 - 2 - 2023 10 - 7 - 2023 end date

	Start Kick off meeting								Midterm evaluation						Greenlight meeting					Final presentation	Back up
Calender week	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Project week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Date	20/02	27/02	06/03	13/03	20/03	27/03	03/04	10/04	17/04	24/04	01/05	08/05	15/05	22/05	29/05	05/06	12/06	19/06	26/06	03/07	10/07
Meetings	February 20		March 10		March 23		april 3		april 18		May 1		May 15		May 30		June 16			July 6	
Discover: research																					
Define: synthesis																					
Develop: ideation																					
Deliver: implementation																					

Draft, continuously revised and updated according to the situation. Ideation will occur in research phase as well; iterating on the research's focus itself.

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.

In recent years I have developed a very sustainable mindset. Throughout my Bachelors and general development, I have come to understand the importance of sustainable design for our future products and services. I get energy from trying to solve these difficult challenges with creative solutions.

Additionally, to me, making the world and our processes, products and services more sustainable all leads back to one thing: energy. Energy is the starting point for everything and is in everything we do. From turning on lights and faucets, to driving cars and flying aeroplanes, to manufacturing all the things we use; it fuels our whole world. Therefore, in order to transition to a more sustainable world, in combination with using energy more efficientyly, first and most importantly, we need to transition to more sustainable forms of energy; the energy transition is urgent.

Since designing and producing everything we use in a circular and renewable way seems so straightforward and self-evident to me, I find it incomprensible that this is not (yet) the case for most renewable energy systems. For these reasons I have gained great interest in innovation within the field of generating and storing green energy in order to make it truly renewable.

Within this project I hope my holistic view, structured approach and creative thinking will be of value and that I will be able to improve my hands-on testing techniques and proactive attitude. Additionally, upon finishing the project I hope to be able to explain common terminology used when discussing composite materials, be able to identify the different types and their relevant qualities and make recommendations regarding their use and end of life. Moreover, I hope to gain valuable knowledge on energy systems, as well as acquiring an understanding of managing a project, both of which can help me in my future professional life. I believe this project is a great combination of my two interest in both the technological side by looking at the blades' material and the business side by looking at large scale applications for the material.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

B. Background information on the Circular Economy

To satisfy growing global needs, the extraction (input of the linear economy) of materials has nearly quadrupled in the last 50 years-(*Circle Economy, 2022*). This is not only accountable for 90 percent of biodiversity loss and water stress (*IRP, 2019*) but is also not sustainable as the world's resources are finite. As described in chapter 1.3, the concept of a circular economy offers a solution to this problem through relooping the resources back into the system at the end of their life.

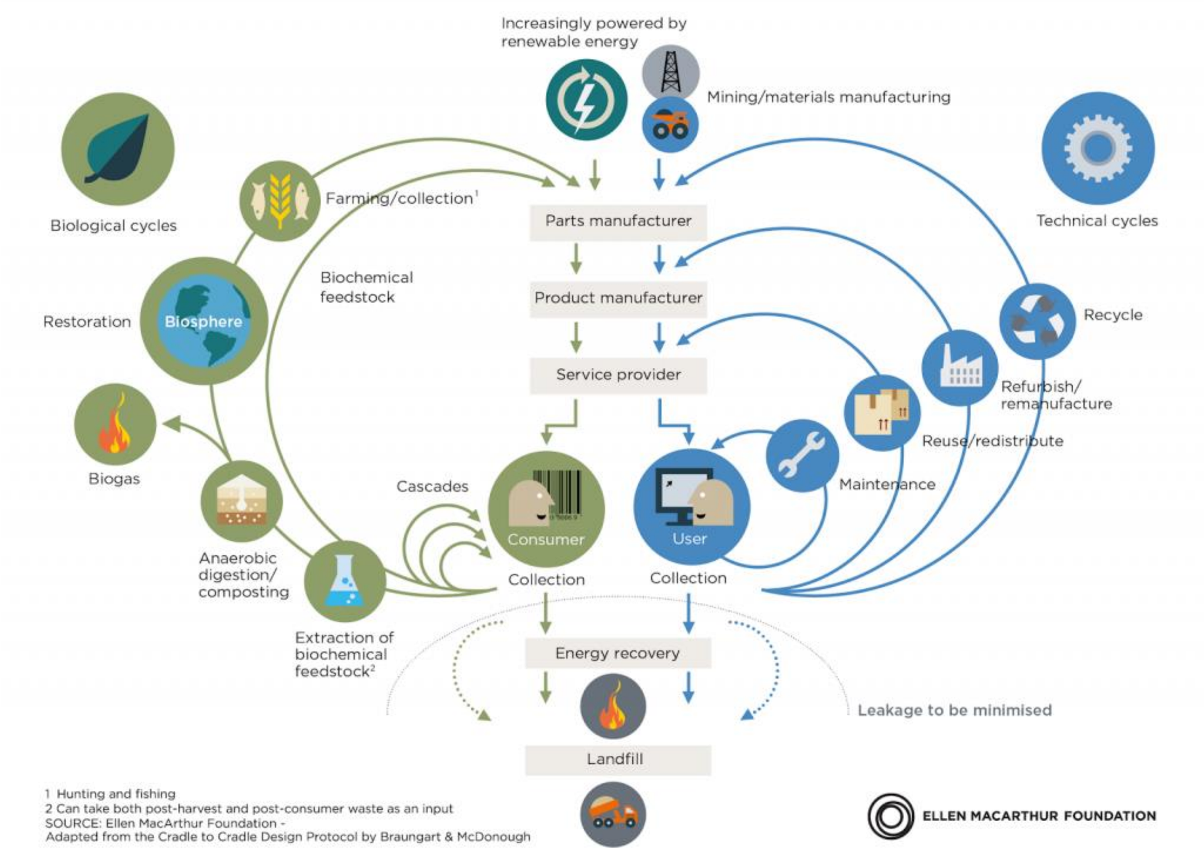


Fig. B1: Visualising the circular economy (*Ellen MacArthur Foundation, n.d.-c*)

There are multiple different frameworks or models with strategies to achieve such a circular economy: The Circular economy systems diagram from the Ellen MacArthur Foundation (*2019*), the EU Waste Framework Directive (*2008*) or the often considered first 'Triple R model' which can be traced back as early as the 1970s (*Pantheon Enterprises, 2016*), to name a few. Additionally, academics have proposed more nuanced models such as the 9Rs framework (*van Buren et al., 2016; Potting et al., 2017*) and the comparable 10R model by Cramer (*2017*). It is up for debate whether the Waste Framework directive and the Ladder of Lansik can still be considered circular as for that disposal or landfill is never an option. This is also already acknowledged by Zero Waste Europe (*Simon, 2021*).

Although one more elaborate than the other, they all share a joint philosophy of aiming to eliminate waste and circling the resources back in a hierarchical way and do so in the most efficient way; preserve the product integrity (*Zhang et al., 2022; Kirchherr et al., 2017*).

Table B1. Overview of different circular economy frameworks

Name	3 R's	Waste framework directive	Ladder of Lansink	Ellen MacArthur Foundation	7 R model	9Rs
Origin	Core of the 2008 Circular Economy Promotion Law of China	Core of the EU Waste Framework Directive	Named after proposal by Dutch Parliament member Ad Lansink	-	Royal HaskoningDHV	Van buren et al. 2016 Potting et al. 2017
Year	2008	2008	1979	2013	unknown	2017
Principles	Reduce Reuse Recycle	Prevention Preparing for re-use Recycling Recovery Disposal	Prevention Reuse Recycle Energy Incineration Landfill	Sharing Maintaining Reusing Redistributing Refurbishing Remanufacturing Recycling	Rethink Reduce Repair Reuse Refurbish Recycle Recover	Refuse Rethink Reduce Reuse Repair Refurbish Remanufacture Repurpose Recycle Recover

Circular economy strategies for composite materials.
However, in relation to products containing composite material the frameworks do not completely hold up. The first principles, which are in relation to preserving the product integrity, can largely be applied. For example, the amount of material needed is reduced because of the advantageous properties of composite material and it can be repaired. Though, in relation to preserving the material integrity, there are little to no options. Most current recycling processes break down the material and with it, its fibres. As a result, the material loses its qualities, leaving a worthless material. This, as described earlier, leads to the most economical option to be landfill or incineration.

To tackle this problem, Joustra et al. (2021b) proposed a circular economy strategy for composite materials. In this he identified structural reuse as a strategy to preserve material integrity. This 5-step framework in the context of wind turbine blades will be elaborated more in the following section, in this most attention goes to the preservation of the material.

Design Aim	*Preserving Product Integrity*			*Preserving Material Integrity*	
Circular economy strategies	Long Life	Lifetime Extension	Product Recovery	Structural Reuse	Material Recycling
Actions / Processes	Physical Durability Long use Reuse	Repair Maintenance Adapt Upgrade	Refurbishment Remanufacture Parts Harvesting	Repurpose Resize Reshape	Remould Mechanical Thermal Chemical

Fig. B2: Framework for circular design of composites (*Joustra et al, 2021b*)

B.1 Long life

Ensuring long product lifetime by promoting **long use** and **reuse** of the product as a whole, through manufacturing **physically durable** products, resisting ageing, fatigue and corrosion, able to sustain wear and tear without failure.

The first strategy is keeping the product in its original state and this way preserve the energy that has been put into making it. Composite material used in wind turbine blades have good fatigue and weather resistant properties making it durable and conforming to the strategy. This is pushed further by the coating that is applied to the material to protect it from environmental exposure. This field is in constant development (*NWO, 2022*), not only to counter the degradation of the material better, but also to increase the efficiency of the energy yield (*Qlayers, n.d.*).

B.2 Lifetime extension

Extending the time in use through **maintenance, repair**, technical upgrading or **adapting**, by users or service personnel. This can be promoted by facilitating handling of the product and subsequent rework tasks.

Wind turbines are designed for a service life of approximately 20 years, but it has been established that most turbines are able to operate beyond this point (*Schumacher & Weber, 2019*). Through analytical evaluations and on-site inspections, the wind turbine can be assessed to forecast and schedule maintenance and repairs. Depending on the type, severity, region and aerodynamic requirements of the damage, these repairs can, for example, entail applying new coating, resin injection for small surface cracks or scarf repairs (*Mishnaevsky, 2019*). Also, replacing some components such as bolts that have worn can be part of this. These repairs can be done both off and on site, with the preference for the latter due to the desire to have minimal down time.

However, besides the determined technical feasibility, the consideration is whether it is still economically viable to continue operating the wind turbine, if it still complies with legislation and what the environmental impact is of continuing the operation or decommissioning and potentially replacing it for a more efficient version (*Beauson et al., 2021*).

B.3 Product recovery

Returning products or parts to working condition, thereby increasing the number of use cycles.

When decommissioned, the product recovery strategy aims to reuse the product and its parts in a way they were originally intended for. Depending on the condition, the decommissioned blades may undergo a refurbishment process. Refurbished blades are in demand as the quality is usually sufficient, the delivery times are short and, naturally, their prices are attractive (*Dutchwind, 2023*). Therefore, multiple platforms exist selling refurbished wind turbines. Potential clients could, for example, be wind park owners that want to bypass downtime if one of their turbines require off site maintenance (*Wraith, 2013*). But projects with the intention of re-deploying refurbished wind turbine blades in the developing world have also been incentivised (*Mazzoni, 2014*). Harvesting parts of the blade for spares or repairs is also a feasible option.

B.4 Structural reuse

Retrieving structural elements, preserving the material composition, through **repurposing, resizing** or **reshaping** product parts for reuse in another context or construction.

As mentioned before, at some point, the blades are at the end of their operational lifetime and need to be decommissioned. Nonetheless, this is more often than not because at this point they can not guarantee the quality anymore as they did not properly monitor it (*Ziegler et al., 2018*), or they are losing their economic viability instead of their technical viability (replacement by larger turbines with more power and/or applying for new subsidies) (*Gauderis & Severijns, 2022*). This means that although they might not be suitable as wind turbine blades anymore, the blades' material properties are still of high quality.

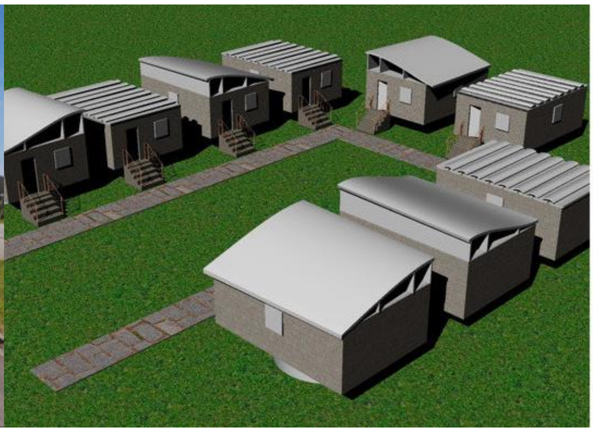
Structural reuse is a concept introduced by Joustra et al. (*2021b*). As brought up earlier and demonstrated in the previous chapters, they recognised that the generic circular economy strategies were largely applicable for the aim of preserving product integrity. However, when the product integrity can no longer be preserved, there is still the need to close the material loop. But instead of directly recycling and losing the valuable embedded specific composite material properties, they identified an additional approach, namely structural reuse. This process discards the original function of the product but preserves the quality and unique properties of the material by repurposing, resizing or reshaping parts either as a whole, or through segmentation in elements, with little effort. This way it prolongs the use of the material, and potentially substitutes use of virgin materials.

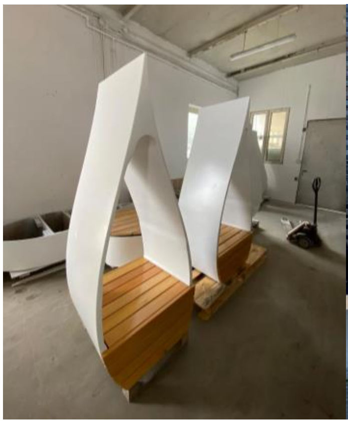
Some initiatives using repurposing, resizing or reshaping as techniques to reuse the material have been brought about, some physically, some theoretically. A quick overview is given:


Pedestrian bridge (*Anmet, 2021*)


Playground (*Superuse, 2009*)

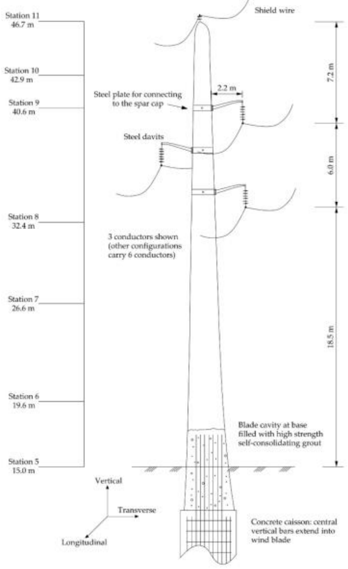

Bike shelter (*Siemens Gamesa, 2021*)


Conceptual housing community (*Bank et al., 2018*)



Lounger (*Anmet, 2021*)

Public bench (*Superuse 2020*)



Blade pole (*Alshannaq et al., 2021*)

Blade table from standardised boards and beams (*Joustra et al., 2021*)

Looking at the cases it becomes apparent that the blade table is the only example really making use of segmentation but that the majority makes use of large parts of the original blade. Due to the intricate shape, integrated material structures and magnitude of the incentives these are often one-offs, hard to use in a diverse range of different applications and difficult to upscale. Accordingly, the amount of repurposed wind turbine blades is negligible in comparison to the volume of decommissioned wind turbine blades entering the market (*Joustra et al., 2021b*). As described in chapter 1.4.1, this is a problem and part of the reason why currently the material integrity is seldomly preserved.

B.5 Material recycling

Recovery of materials through **thermal, chemical**, or **mechanical** processes, resulting in raw materials ("recyclate"), aiming to close the materials loop.

The recycling of the material is the "loop of last resort" and should be avoided by designing products to be suitable for the above-mentioned strategies (*Ellen MacArthur Foundation, n.d.-b*). Nevertheless, it is a necessity if the material's lifetime comes to an end in order to make the material's life cycle circular. Recycling returns the material at the end of its life to usable raw material.

The matrix material being a thermoset polymer is for a large part responsible for the challenges at the end of a composite's life. Other than thermoplastics, thermosets are not remouldable when exposed to heat and often degrade before melting. This makes it hard to separate the fibre reinforcements from the matrix at the end of its lifetime and return to the original constituents (*Gonçalves et al., 2022*).

Companies and research institutes are developing ways involving mechanical, thermal and chemical ways of recycling the composite material. These are amongst others processes like solvolysis and pyrolysis with the goal of retaining the long fibres. Mechanical recycling in which the material is shredded and thus the fibres are cut and most of the material integrity disappears is the most mature option (Y*ang et al., 2012*). Examples of applications for this are, amongst others, the cement kiln route in which the shredded blades are added to the kiln to create the cement (*General Electric, 2020*), the use as reinforcing elements which in combination with virgin resin and fibre to enable the production of a brand new component (*Busschen, 2021*) and Fused Filament Fabrication (FFF) which has the goal of improving the mechanical performance of 3D printed components (*Rahimizadeh et al., 2019*). However, as with these processes no raw materials are extracted it is questioned whether the terminology of recycling applies to these methods.

Running through other ways of recycling wind turbine blade material. Pyrolysis makes use of heat and often vacuum to decompose material. Multiple sorts of pyrolysis have been developed and TNO has been able to extract the fibres from blades (*Van Weezel, 2022*). Solvolysis makes use of a chemical solvent to break down the material. Rani et al. (*2022*) obtained promising results using a sustainable microwave-assisted chemical recycling process using hydrogen peroxide and acetic acid to recycle glass fibre reinforced polymers. However, most recycling initiatives are mainly still on laboratory scale and unable to preserve the material quality as, for example, the strength or strain of the glass fibres are only a portion of what they originally were (*Leon, 2023*). This small scale makes retrieving the original materials not viable (yet) (e.g., due to low price of virgin glass fibres).

Today the most common recycling activities involve little to no material recovery (Y*ang et al., 2012*) and are 'waste to energy' incineration and the lowest of the waste hierarchy: incineration or landfill, the latter of which has already been banned in a number of countries. Both do not allow for re-entering of the materials and have negative effects on the environment (*Leahy, 2020; source*).

To address the problem at the root and facilitate easier recycling, research in the use of alternatives to the currently applied thermosets is being done too. Vestas (*2023*) has unveiled a circular epoxy-based turbine blade, Siemens Gamesa (n.d.) has too and so did LM Wind Power with Arkema's Elium resin (ZEBRA, 2022). These could provide a material recovery solution for in the future. But it can be concluded that for the turbines that are up and running today and are likely to be installed in the next 5-10 years, there are little to no recycling options that are both viable and desirable.

C. Initial delamination exploration of sandwich structures

Through consulting literature an initial understanding of the methods for delamination of a sandwich structure was gained. Four different approaches were found to have potential, the fifth: separation through pressured air was the result of a discussion with Albert ten Busschen (*personal communication, 17 April 2023*The different approaches together with experiments exploring these principles will be elaborated.

C.1 Mechanical separation

The skin laminate and core material can be separated by applying force in a certain direction. The fracture toughness describes the material's resistance to crack propagation and thus delamination (*Zehnder, 2012*) and is different for different stress orientations. A lower fracture toughness could presume easier separation. Adhesively bonded elements are typically relatively strong under tension, compression, and shear loading, but less strong in cleavage and peel (*Yacobi et al., 2002*). With the goal of delaminating, **cleavage and/or peel stress might be exploited.** Additionally, cutting or sawing techniques are an option too although it is presumed that this might face difficulty with double curved parts.

A quick and easy test was conducted to examine the feasibility of mechanical separation and the desirability of the results. The following research questions were tested:

1. To what extent can the laminate be separated from the core?
2. What is the result of the delamination?
3. Where does the separation occur?

This has been tested by hitting a chisel (width 10mm) in between the core (balsa wood) and skin of a test sample retrieved from a wind turbine blade.

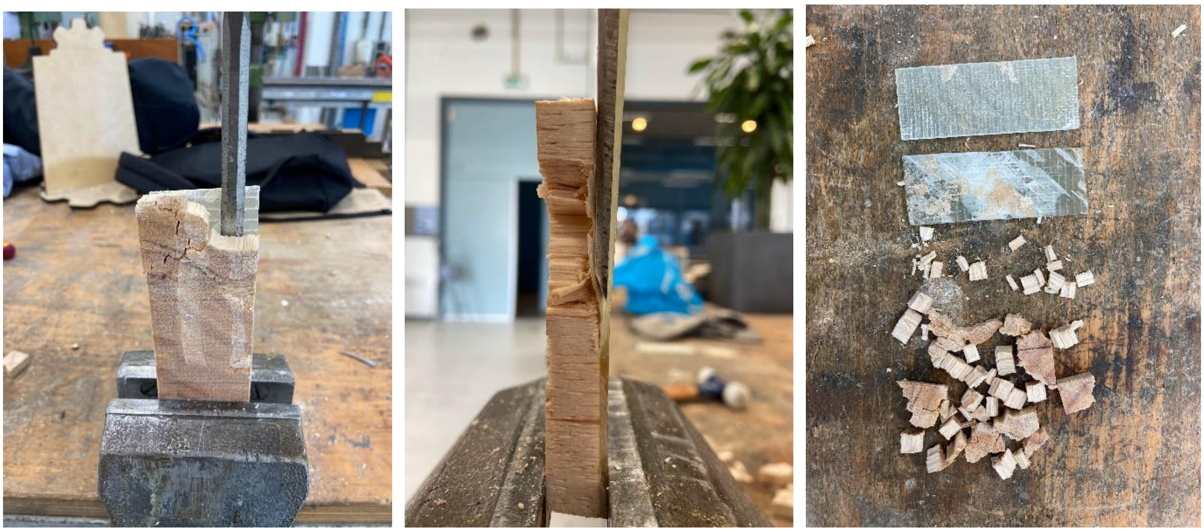


Fig. C1: Result of mechanical separation

It was concluded that the laminate can in fact be separated from the core, although this happens more easily and cleanly at one side than the other. The result of the delamination for one side is a rather clean-cut piece of laminate, although when delaminating the other side, the wood crumbles. This is possibly because it is no longer held together by a laminate. Also, regarding this side, the laminate itself delaminates. As a result, delamination is more difficult and less clean. The delamination does happen primarily at the surface between the core and skin material.

Another test was conducted to quickly test whether the fact that delamination appears to be more difficult at one side than the other is because it is delaminated second, or because actually one and the same side is more difficult to delaminate than the other. This was done in a similar fashion to the previous test but starting by separating the other side first.

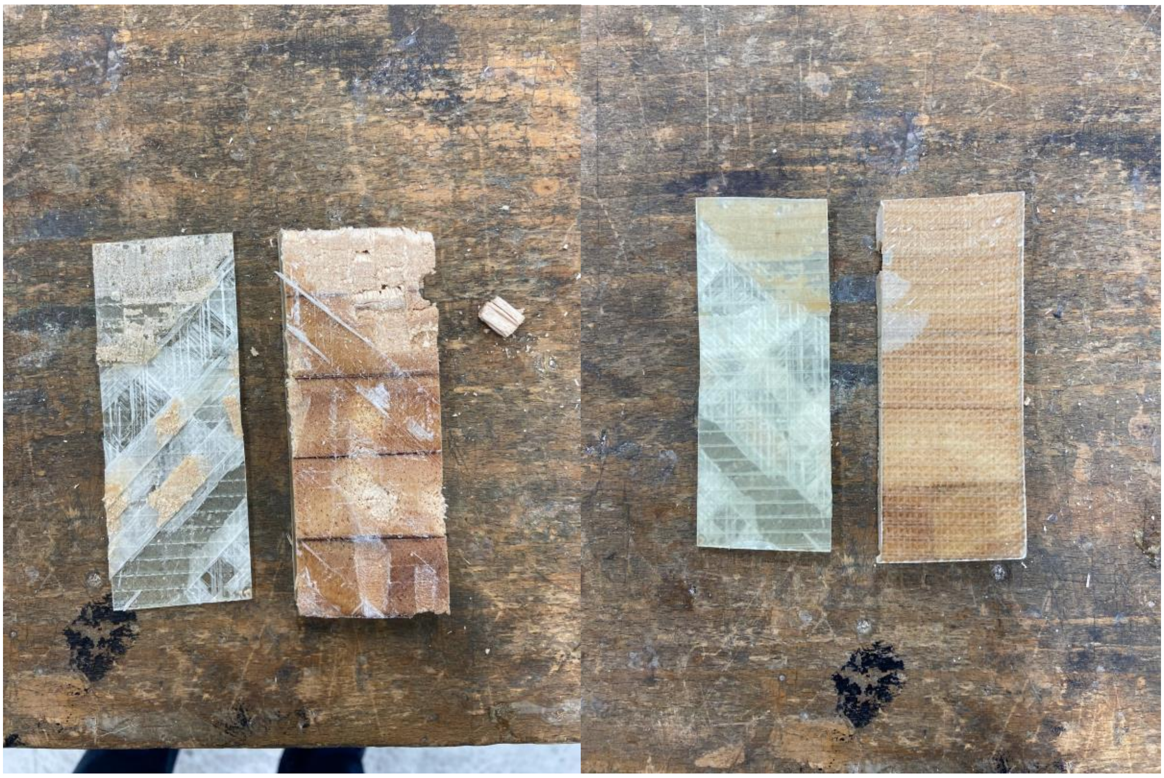


Fig. C2: Result of testing difference in laminate side

The test showed that delamination was again harder on the same side. Therefore, it being the first or second side to be delaminated did have little to no influence. During delamination of the second side and in this experiment the better side, the balsa wood core material came off in bigger parts. This is possibly because it was still held together by leftover epoxy and fibres due to the faulty delamination. Potential explanations for the difference in delamination between both sides of the sandwich sample are discussed in chapter 4.2.1.

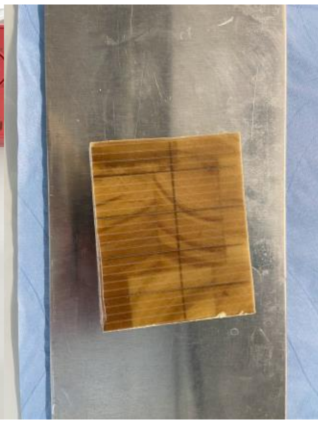
Mechanical separation was concluded to have potential. The feasibility was shown, and the results of the delamination could be of use for reuse applications. As described, cleavage and peel stress are said to be promising to exploit, but the quick and easy tests also showed the potential of wedging.

C.2 Thermal separation

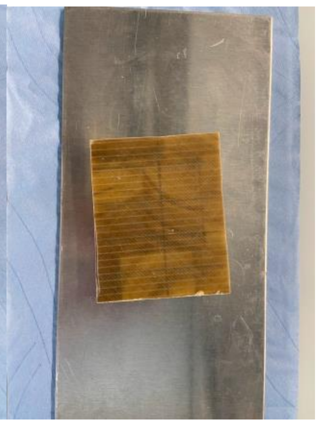
Temperature can influence the material properties of the core and skin laminate, and the adhesion between the two. Heating it up might soften the material while cooling it down might make it more brittle. Studies have shown that the fracture toughness is temperature dependent and increases with an increase in temperature (*Toygar & Maleki, 2016; Walter et al., 2001*). Simultaneously, the adhesion strength decreases when above the glass transition temperature (T_g) (*Akulichev et al., 2017*) and although thermosetting plastics degrade before they reach their melting temperature (transition of solid into liquid), they often do undergo glass transition (transition from solid into rubber-like state). Therefore, there lies potential in using heat as a method for delamination.

Additionally, the core and skin materials might have different thermal mechanical properties. For example, the coefficient of thermal expansion is the amount with which the size of an object changes in relation to a change in temperature. If either of the two has a significantly higher thermal expansion coefficient, the material's volume might increase disproportionately to the other, causing stresses between the two materials. These stresses might induce delamination. Tempelman (*1999*) demonstrated the potential of this technique by separating aluminium foils from epoxy resin and glass fibres, using the large difference of thermal expansion coefficients between the material.

A quick and easy test was conducted to evaluate the above-mentioned aspects and thereby examine the feasibility of thermal separation and its results. This has been done by placing a sandwich sample (balsa wood core) in an oven and increasing the temperature starting from 90°C to 100°C to 125°C to 150°C to 175°C every 15 minutes. In between the sample was taken out the oven and examined.



After 150°C



after 175°C

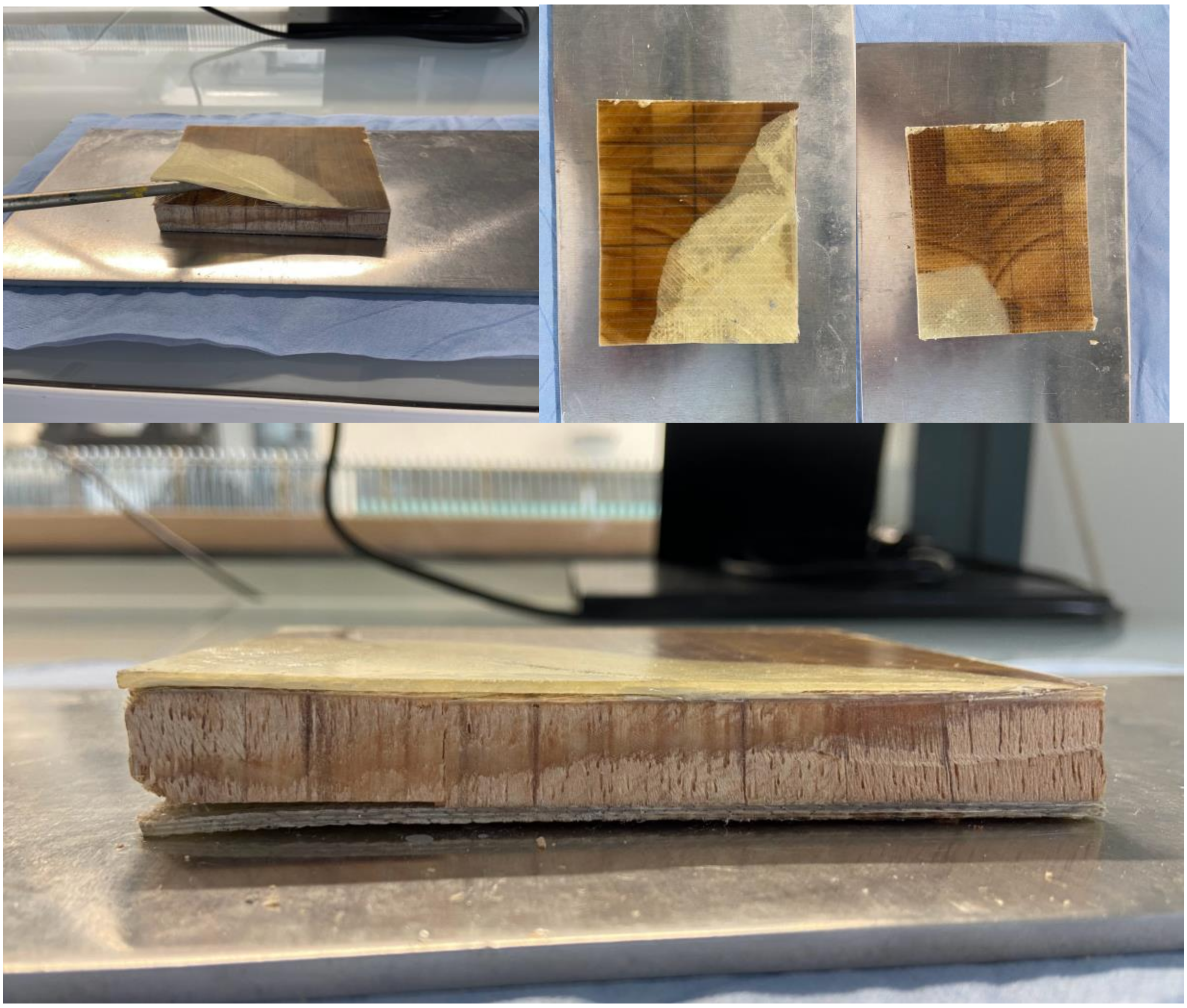


Fig. C3: Sample after exposing to heat and delamination attempts.

Up until a temperature of 150°C no visual or physical changes were observed. At 150°C the laminate seemed to soften a bit. At 175°C the laminate appeared duller and more flexible and was easier to peel off. However, because the separation of the skin from the core material was conducted outside the oven, the sample quickly cooled, making it difficult to continue peeling for a longer time. As a result, the laminates remained plastically deformed.

However, the question is whether the quality of the peeled off laminate layer is sufficient. Heating of material degradates its strength and stiffness (*Vasiliev & Morozov, 2018*). The visual change in the material (browning and becoming dull) is also a sign of the degradation of the material, negatively affecting the material properties (*Julie Teuwen, personal communication, 22 March* 2023) Therefore, although temperature might enable delamination, the results are not desirable.

C.3 Hydrologic separation

Water can have an influence on the material. The water might degrade material properties making delamination easier, or potentially, absorption of water is accompanied by expansion (*Li & Weitsman, 2004*), creating stresses and enabling delamination. There lies extra potential in combining hydrologic separation with temperature. Firstly, because the diffuse process of water goes with the square root of the temperature and boiling hot water might therefore wet the core material better. Secondly, when cooled below freezing temperature, the water expands, potentially inducing stresses and enabling delamination.

This has been explored through quick tests by submerging a sample (balsa wood core) in water for about 24 hours at room temperature and submerging a sample in boiling water for about 1 hour and then attempting to mechanically separate the laminates from the core for both samples using a chisel.

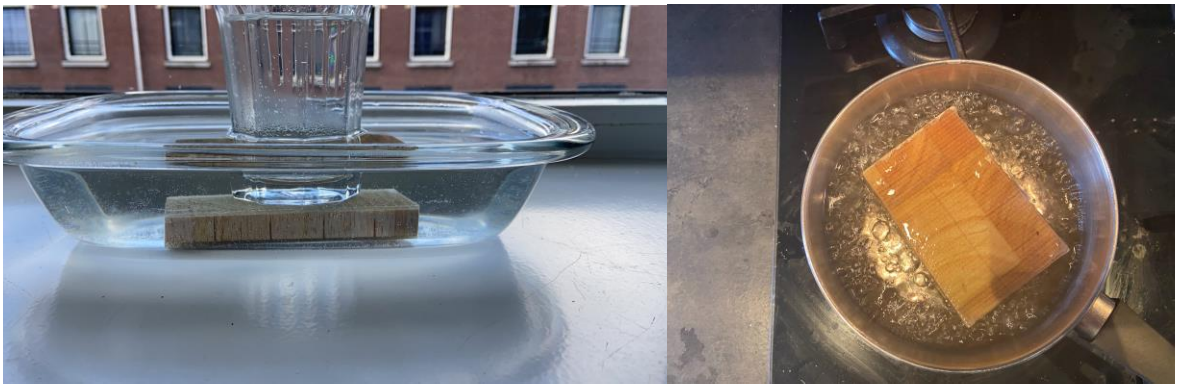


Fig. C4: A sample submerged in water.

No visual changes were observed after submerging the sample in water at room temperature. The laminates from the sample submerged in boiling water appeared to slightly darken. However, in both instances, a wet core was not considered beneficial for mechanical delamination. No induced stresses were experienced, and the degradation of the balsa wood resulted in the core material becoming less stiff and brittle, making it more difficult to achieve a clean separation using a wedge.

Possibly, the core material was difficult to get moist due to the small contact area with the water, and the orientation of the nerves. Additionally, the laminate on both sides of the core material might balance out the stresses induced by the expansion of the core material due to water absorption. Therefore, the tests were repeated with samples that had one laminate removed already.

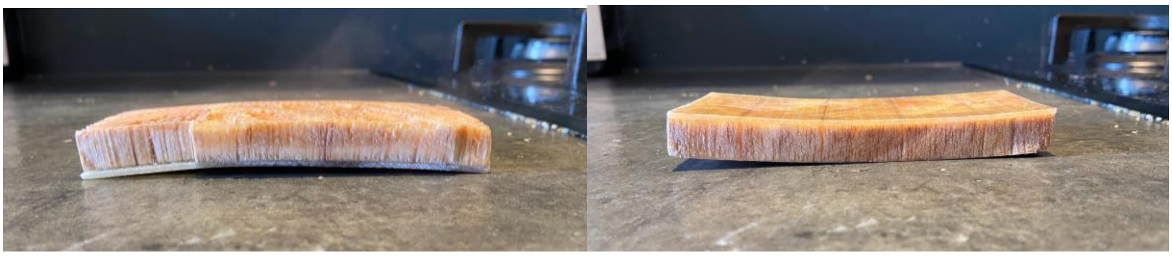


Fig. C5: Samples submerged in water with one open side

It was observed that the samples bend. Although no direct delamination happened, it seems like the balsa wood core has expanded and exerted stresses, causing the sample to deform. This substantiates the above made hypothesis. However, still it was not beneficial for mechanical delamination.

Lastly, a sample with an open core that has been submerged in water was placed in a freezer to quickly evaluate if it had any positive effects. Nevertheless, no visible results were observed. It is possible that the influence might be too little, or the temperature might not be cold enough.

C.4 Chemical separation

Chemical separation can be done by weakening the adhesion or removing either the core material or the laminate. For the purpose of the project, the latter is not an option. But also removing or dissolving the core material is not desirable as this is not in compliance with the circular economy. The feasibility and viability of weakening the adhesion through a chemical substance is questionable as it is hard for the substance to permeate the sandwich structure and get between the surface between the core and the skin, similar to as discussed with water.

Quick tests conducted with (cleaning) acids gave no tangible results for a sandwich structure with a foam core in both instances: one 'normal' sample and one sample with one side pre-delaminated. It is likely that the type of medium was not strong or aggressive enough. Processes like solvolysis have demonstrated that the use of chemicals can be an effective technique to delaminate sandwich structures. However, because of the absence of promising results, the uncertainty about the usability of the material resulting from chemical separation, the minimal familiarity with the matter and limited access to the supplies, it was decided not to pursue this direction further as part of the project.

C.5 Separation through pressured air

With Albert ten Busschen the potential of using pressurised air to delaminate one side of the sandwich structure was discussed. By drilling a hole through one of the laminates and applying compressed air through the hole you could potentially blow the laminate off the core. For this there can be no leak and the size of the sandwich structure should not be too small else you get passages for the air to flow away.

A quick test applying compressed air to a hole drilled in the laminate of a 20cm-by-20cm balsa wood sandwich structure did not appear promising: no delamination occurred. It may be that there was a form of leakage through either the hole or de sides, or that the equipment used was inadequate. Therefore, it could be interesting to experiment with this in further research. Nevertheless, because of similar argumentation as for the chemical separation, it was decided not to consider it in this project.

C.6 Conclusion

From the literature and quick and easy tests it became apparent that mechanical separation was possible, temperature can ease the process of delamination but degrades the material at the same time, hydrologic separation and separation using pressured air did not have beneficial effects and chemical separation does not seem suitable for the desired outcome. Therefore, it is concluded that mechanical separation, more specifically peel, cleavage and wedge, are the most promising to pursue further.

The test mainly explored one separation technique; in future research it is interesting to try out combinations. Also, the delamination tests have been done using relatively small samples. It is assumed to be representative for larger sized panels as well, although that would probably require more force. However, future research is needed to substantiate this.

D. Bending experiment

Finding the minimum bending radius of laminates retrieved from sandwich panels.

It is assumed that composite laminates have a certain degree of flexibility which can be exploited and allow for more design freedom in the creation of reuse applications. This flexibility can be achieved by bending the material, which has been determined as the change in the radius. Initial experimenting with the material revealed that a quadraxial GFRP laminate was able to bend 180° with a radius of 50mm. A test regarding the flexibility of these laminates is conducted in order to quantify this bending and determine the upper limits so that it can be of use in the design process.

Research questions

The following research questions will be addressed:

1. How far can a laminate retrieved from a wind turbine blade bend?
2. Is there a difference in bending behaviour in different orientations?

Materials and methods

The tests were performed in the PMB at the IDE faculty of the TU Delft. GFRP laminates were retrieved by delaminating a sandwich structured composite. Four different types of laminates were used for the tests. The samples had a thickness of 3mm, similar to laminate thickness of the potentially retrieved elements from the wind turbine blade.

Table D1. Parameters

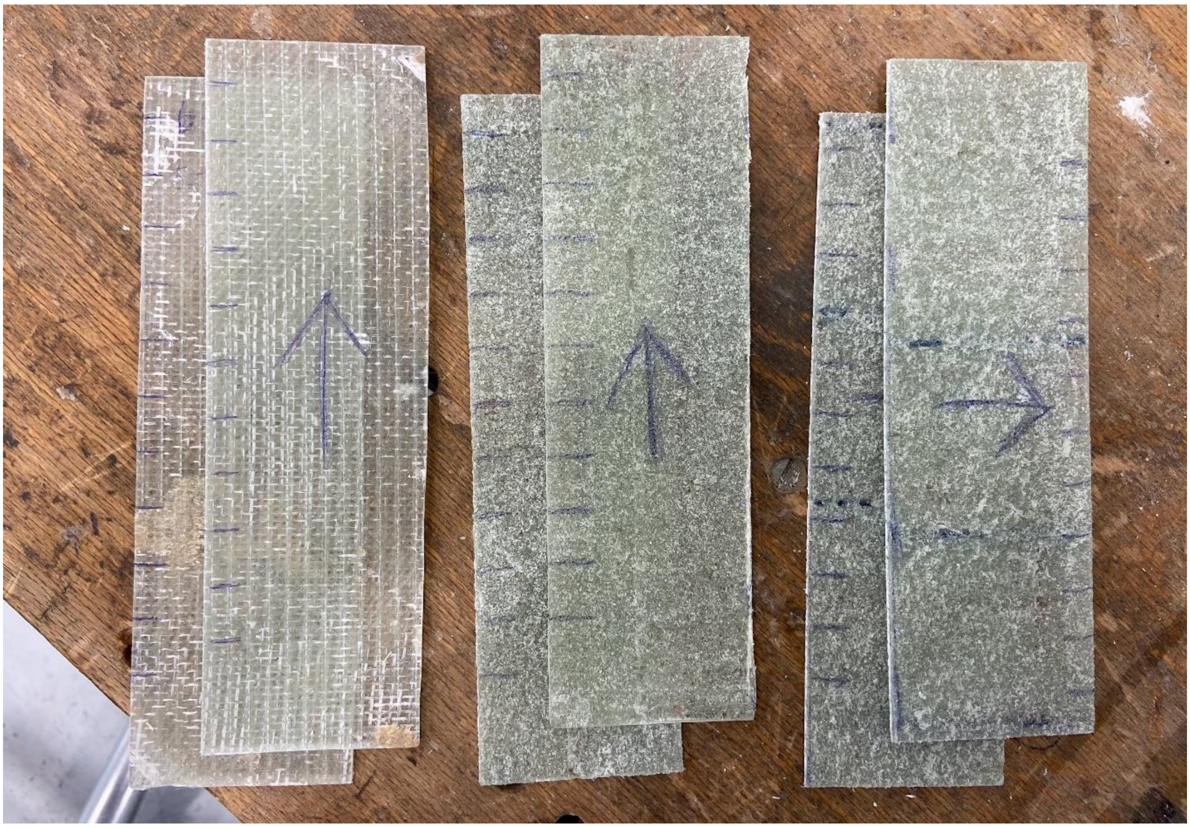
Laminate	Fibre layup	Orientation	Width	Length	Thickness
1	Biaxial	0°	60mm	200mm	3mm
2	Biaxial	90°	60mm	200mm	3mm
3	Quadraxial	0°	60mm	200mm	3mm
4	Biaxial	0°	40mm	200mm	3mm

The minimum bending radius, the minimum radius to laminate can bend before it fails, is determined by stepwise decreasing the bend radius of the laminates in steps of 5mm. The laminates are bent to 180° at which the chord length is the diameter, which allows for convenient measuring. Two laminates of each type are tested to test the influence of the bending direction: if the laminates are imagined still with the core attached to them, one is tested by bending towards the core and the other is tested by bending away from the core.

Since initial experimenting with the material revealed that a quadraxial GFRP laminate was able to bend 180° with a radius of 50mm, around this ballpark was taken as a starting point for finding the minimum bending radius. 60mm was chosen as the starting radius. This equals an arc length for half a circle of 189mm. Taking into account a minimum of 10mm for clamping the laminate, a total length of 200 was chosen for the laminates. The laminates were cut to size with a lever shear.

The corresponding arc length for the to be tested radii were marked on the laminates in order to be able to match the right arc length with the right diameter and achieve the right radius of the created circular curvature. Figures D1 and D2 show the laminates and the test setup.

Fig D1. The laminates used.



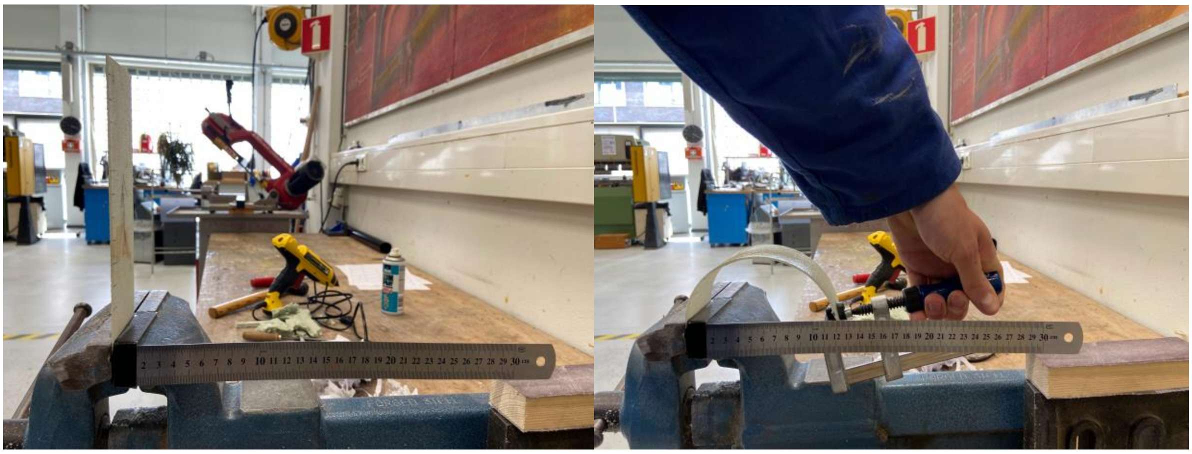


Fig D2. Test setup

Results

Table D2. Results of bending test

Sample	Type	Width	Orientation	Bending direction	Min radius	Arc length
1	Quadraxial	6mm	0	Inwards	10*	30
2	Quadraxial	6mm	0	Outwards	10*	30
3	Biaxial	6mm	0	Inwards	32	100
4	Biaxial	6mm	0	Outwards	25	80
5	Biaxial	6mm	90	Inwards	13	40
6	Biaxial	6mm	90	Outwards	19	60
7	Biaxial	4mm	0	Inwards	22	70
8	Biaxial	4mm	0	Outwards	25	80

Minimum bending radius

- Bending along fibre orientation: ≈ 32mm
- Bending perpendicular to fibre orientation: ≈ 19mm

* Deterioration of the samples began at a radius of 30mm. At this point the sample started to creak, and delamination started to occur.

Regarding the point of failure, for the quadraxial samples the breaking happened at the clamping points. For the biaxial samples the breaking occurred along the arc.

Conclusion

Answering the first research question, from the experiment it can be concluded that the laminates can bend to a small radius (largest = 32mm). It can moreover be concluded that there is a difference between the minimum bending radius of the quadraxial and biaxial samples; the quadraxial samples were able to reach smaller bending radii. However, it should be noted that although they only broke at a radius of 10mm, deterioration of the sample started to happen earlier. This evens out the results. Furthermore, answering the second research question, the orientation of the fibres has an influence on the minimum bending radius; the 90° orientated samples were able to achieve smaller bending radii. Also, it appears that the width of the sample has a slight influence on the bending radius of the laminate: a smaller laminate can achieve smaller bending radii. Lastly, the bending direction appeared not to have a significant influence on the results.

It should be noted that the results are not indisputable. The main goal of the test was to get an insight in the bending properties of the material and the order of magnitude. Future testing with a larger sample size and e.g., larger and thicker laminates is required to gain exact and more detailed knowledge on the bending capabilities of the material.

E. Full datasheet tensile tests

	Speed, tens	Maximu	Test speed	Pre-load	Specimen no.	h	b	A0	Peak detection	Date/Clock time	L0 CH	Type of failure	Displacement at	Strain at maximum	Tensile strength	Young's modulus
	mm/min	mm	mm/min	N		mm	mm	mm²	N		mm		mm		MPa	GPa
Straight																
Specimen 2	5	3	5	0,1	2	3	10,9	32,7	6713,02	45071,64715	150,9061411	Invisible	4,494002342	0,02978011571	205,2909828	7,577918496
Specimen 3	5	3	5	0,1	3	3	9,8	29,4	6869,51	45071,65025	150,4165691	Invisible	4,944349289	0,03287104153	233,656911	7,827728371
Specimen 4	5	3	5	0,1	4	3	9,8	29,4	6290,11	45071,65388	151,0081366	Invisible	5,280564785	0,03496874342	213,9493649	6,415465124
Specimen 5	5	3	5	0,1	5	3	9,7	29,1	6106,89	45071,65676	150,7771296	Invisible	5,240185738	0,03475451319	209,8586166	6,689970312
Specimen 6	5	3	5	0,1	6	3	10,6	31,8	7635,14	45071,6594	151,1656684	Fracture	5,141934395	0,03401522614	240,0987618	7,589134555
Average								*30,48*	*6722,93*		150,8547289		*5,02020731*	*0,033277928*	*220,5686746*	*7,220043372*
Radius x3																
Specimen 7	*5*	*3*	*5*	*0,1*	*average*	*3*	*10,3*	*30,9*	*6342,30*			-	*4,3734915*	*0,0290736*	*205,2525157*	*7,4710*
Specimen 8	5	3	5	0,1	8	3	10,3	30,9	5687,70	45077,59382	150,2646083	Invisible	4,252692223	0,02830135632	184,0680939	7,081933122
Specimen 9	5	3	5	0,1	9	3	10,3	30,9	6996,90	45077,59612	150,5835974	Fracture in middle	4,494290829	0,02984581924	226,4369374	7,86016406
Specimen 10	5	3	5	0,1	10	3	10,3	30,9	7405,58	45077,59872	150,533579	Fracture in middle	5,286991119	0,03512167289	239,6627225	7,041302332
Specimen 11	5	3	5	0,1	11	3	9,8	29,4	7132,07	45077,60223	150,5942912	Fracture in middle	4,708739281	0,03126771435	242,5875585	8,00638519
Specimen 12	5	3	5	0,1	12	3	10,5	31,5	7332,00	45077,60534	150,4392664	Fracture in middle	4,841283321	0,03218098198	232,7619203	7,637659675
Specimen 13	*5*	*3*	*5*	*0,1*	*average*	*3*	*10,2*	*30,6*	*7891,65*	*45077,61*		-	*4,8798997*	*0,0324243*	*257,8971035*	*8,2428*
Specimen 14	5	3	5	0,1	14	3	10,2	30,6	7155,01	45077,60941	150,3839851	Invisible	4,821766376	0,032063031	233,8237528	7,713058981
Specimen 15	5	3	5	0,1	15	3	10,2	30,6	8628,30	45077,61098	150,615794	Fracture at clamping	4,938033104	0,03278562607	281,9704542	8,7726183
Average								*30,66*	*7220,72*				*4,8180810*	*0,0320137*	*235,5095038*	*7,6798*
Radius x2																
Specimen 16	5	3	5	0,1	16	3	10	30	6909,21	45077,61819	150,6879543	Invisible	5,000364304	0,03318357015	230,3069499	7,424715894
Specimen 18	5	3	5	0,1	18	3	10,6	31,8	8495,20	45077,62206	151,1363081	Invisible	5,082249165	0,03362692413	267,1447216	8,182225486
Specimen 19	5	3	5	0,1	19	3	9,4	28,2	7085,76	45077,62453	150,7706712	Fracture	4,827287197	0,03201741532	251,2680075	8,022273298
Specimen 20	5	3	5	0,1	20	3	9,3	27,9	7056,43	45077,63079	150,2540476	Fracture	4,738902092	0,03153926411	252,9186793	8,22851394
Specimen 21	*5*	*3*	*5*	*0,1*	*average*	*3*	*12,3*	*36,9*	*7563,97*			-	*4,231838942*	*0,02808315297*	*204,9855037*	*7,9261*
Specimen 22	5	3	5	0,1	22	3	12,3	36,9	6694,39	45077,63947	150,7396669	Invisible	3,714457512	0,02464153988	181,4198398	7,805987701
Specimen 23	5	3	5	0,1	23	3	12,3	36,9	8433,54	45077,64337	150,6504557	Invisible	4,749220371	0,03152476605	228,5511676	8,046271173
Average								*30,96*	*7422,11*				*4,77612834*	*0,03169006533*	*239,7323301*	*7,956771611*

Figure E1. Values from tensile tests

F. Ideation exploration