Demonstrating re-use of thermoplastic composites originating from wind turbine blades

Karel Brans
Integrated Product Design
MSc. Graduation Thesis

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Preface

The thesis before you is the result of my graduation project to obtain my Master of Science degree in Integrated Product Design at the Delft University of Technology. Around one and a half years ago I was helping Jelle Joustra, who became my future mentor, in his research on flattening thermoplastic composites to connect composites with the circular economy. Having both a passion for materials, composites in particular, but also knowing the immense impact of these materials on the environment, I very much enjoyed this research and working with Jelle. Walking through the faculty we met Ruud Balkenende, Jelle's co-promotor, who asked me if I would like to graduate on a similar topic. This got me thinking and a couple months later I submitted my first graduation project brief. This project gave me the feeling I was making a real contribution to developing the circular economy for composites, a great motivator. Making use of easily accessible, state-of-the-art knowledge, and machinery, this was the graduation project I hoped for.

This project wouldn't have been possible without the help I received from various people and companies. First, I want to thank my supervisory team, starting with Ruud. Though always busy and flying from one meeting to the next, he still found time to delve into my project and give spot-on and direct feedback, pushing and guiding me along. Secondly Jelle, always open for a cheerful discussion, and providing relevant information and his personal network. I could not have had a better combination of chair and mentor with the amount of on-topic knowledge and enthusiasm you both brought.

I would also like to thank all the experts I consulted with during the project starting with Julie Teuwen from the TU Delft for her expertise in wind turbines and composites. Pierre Gerard from Arkema for providing me with the Elium resin and information. Erwin Duits and Albert Rijtsema from Heijmans, Vincent Alberts from Hydro and Dick Breederveld for their help in acquiring knowledge about lampposts, the multiple sparring sessions, and providing the luminaire of the demonstrator. Simon Joncas and Louis-Charles Forcier from École de Technologie Supérieure and Sybren Jansma from LM Wind Power for providing design information about thermoplastic composite wind turbines. Tahira Ahmed from Curveworks, for consultation on shaping composite sandwich panels. Philippe van der Pal of the TU Delft for providing me with a composite workplace. PhD candidate Israel Carrete for the fruitful discussions about the setup and results of the research. The always helpful staff of the workshop at my faculty (PMB) for helping and mostly letting me experiment on the reshaping process.

I also want to thank my family and friends who unconditionally supported me during the project. My parents for motivating me and helping where possible. Clint, Demy, Emma, Gijs, Jennifer, Mar, Mart, Matthijs, Neva, Roan, both Rubens, Sam, Sander and Teye, my Delft squad for their mental support, many coffees and 'Kafees', good times filled with laughter. My roommates and friends Bob and Jimmy for contributing to me feeling 'at home' and enduring my complaining about the project. Lastly, I want to thank my high school friends Bas, Dewi, Dustin, Eva, Rachel and Tanne who I know I can always rely on.

I hope you will enjoy this thesis, and hope you will start to consider the opportunities made possible by reshaping thermoplastic composites!

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Glossary

Acronyms

- EOL	End of life
- GF	Glass fiber
- TPC	Thermoplastic composite
- TSC	Thermoset composite
- UD	Uni directional (fibre orientation)
- WTB	Wind turbine blade

Terms

- Forming limit	The limit of the extent of forming a material before it creates defects.
- Matrix	'Binder' material between the fibers
- Monolithic structure	Structure consisting only of the fibers and matrix material
- Ply	One layer of composite material
- Recyclate	Material diverted from the waste stream during a manufacturing process
- Sandwich structure	Structure consisting of plies and a core material to increase stiffness
- Tg	the temperature at which an amorphous polymer changes from a hard/glassy state to a soft/leathery state

Summary

The goal of this thesis project was to explore how material originating from thermoplastic composite wind turbine blades (TPC WTB) can be reshaped. The insights gained during exploratory activities were used to design a re-use application. The demonstrator model should inspire people to develop other applications and build upon the foundations laid here.

While wind turbines are a big contribution to the green energy supply, their blades form a problematic waste stream of hard to recycle material. One upcoming blade design innovation aimed at enhancing recycling, that of thermoplastic composites, has opened up a new opportunity in circular end of life strategies: structural re-use through reshaping.

A reference TPC blade was drafted based on insights gained from literature and experts, which defines characteristics like material composition, structure and curvature. These were needed for subsequent material tinkering activities aimed at understanding the material, exploring forming limits and process parameters (Figure 1).

Figure 1 Samples made during material tinkering activities

These findings, together with material properties and opportunities and threats were combined in a SWOT matrix and design requirements. Blade segmentation was used to make a panel classification table which contains information on panel characteristics which were later used in designing an application. To be able to shape smaller radii, it was decided to split the top layers from the sandwich panel which resulted in much thinner laminates but also more unused material (15 wt%).

After a solid understanding of the material was built, an application could be designed. Standard ideation tools like brainstorming were used but also less standard methods aimed at finding applications yielded diverse application ideas. Following the design vision, one idea was selected: a lamppost. Embodiment of the lamppost based on earlier findings and a norm resulted in a conceptual application design. To prove the feasibility of this application, the strength and stiffness of the post were calculated to comply with the NEN EN 40 norm.

This design was translated to a demonstrator which can be seen in Figure 2. The goal of this demonstrator was to evaluate the performance of the material in reshaping and to simultaneously inspire people to develop new applications, which was validated using interviews. An evaluation of the amount of material used in this application showed that about a third of the yearly supply of WTB material saturates the yearly demand of lamppost.

It can be concluded that the material performs well in reshaping single curved geometries, however reshaping could be problematic for double curved surfaces. The smallest single curved radius tested was 30mm while the largest double curved radius which was tested was 1000mm. A meaningful application which makes use of the material's value can be made within the reshaping limits while also utilizing a significant amount of blade waste.

Figure 2: The demonstrator lamppost reshaped from simulated TPC WTB material

1. Introduction

The first part of the thesis report describes the overarching problem of wind turbine blade end of life (EOL) and its key considerations. This is followed by the introduction of fitting circular strategies which could help reduce the problem of wind turbine blade waste and how these strategies are currently integrated in wind turbine end of life considerations. From this a knowledge gap is identified which forms the basis of the project mission. Research questions are then set up and the project is scoped. Lastly the approach of the project is discussed.

1.1 The problem of Wind Turbine Blade waste

Wind energy looks to be an increasingly valuable resource in the search of green energy. As many governments worldwide support the implementation of wind turbines, the production of this equipment has increased drastically (Liu & Barlow, 2017). Currently most turbines are expected to last for 20 to 25 years with ongoing research to prolong this lifetime (Ziegler, Gonzalez, Rubert, Smolka, & Melero, 2018).

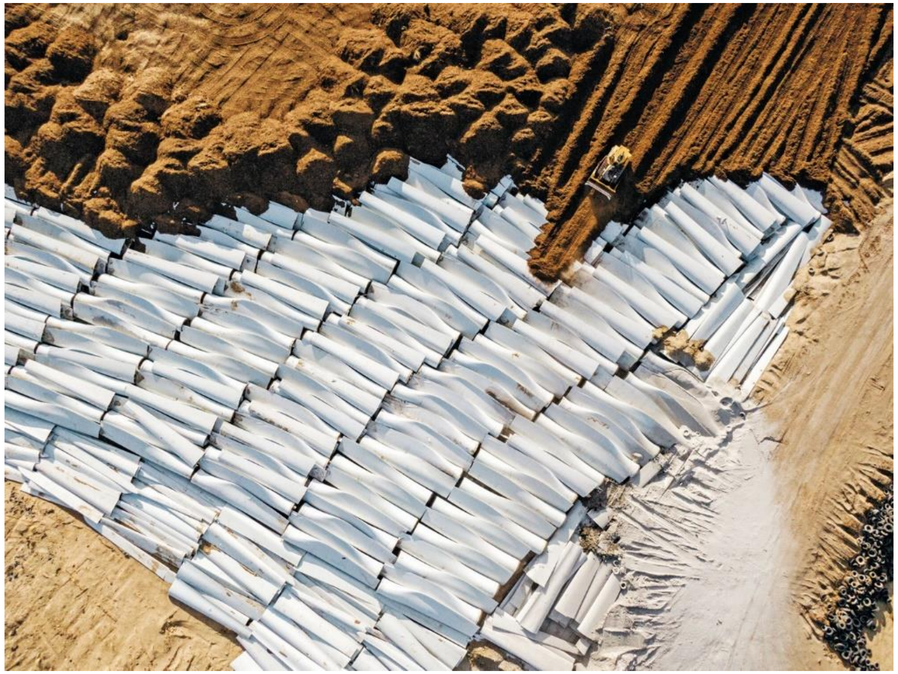

Figure 4 Partially sectioned wind turbine blades being covered by dirt as landfill (Jacoby, 2022)

While most components of the wind turbine can be recycled well, the wind turbine blades (WTBs) cannot (Andersen, Bonou, Beauson, & Brønsted, 2014). This is further discussed on page 12. Because of these recycling complications, most blades end up either as cement kiln or landfill which can be seen in Figure 4 (Larsen, 2009).

A waste stream of hard to recycle material is growing at an increasing rate. One study expects around 3.5 Million tons of blade material will be used in 2050 with blade waste reaching over 2 Million tons that year as Figure 3 shows (Liu & Barlow, 2017). These numbers are concerning when problems in the disposal of wind turbine blades are not solved.

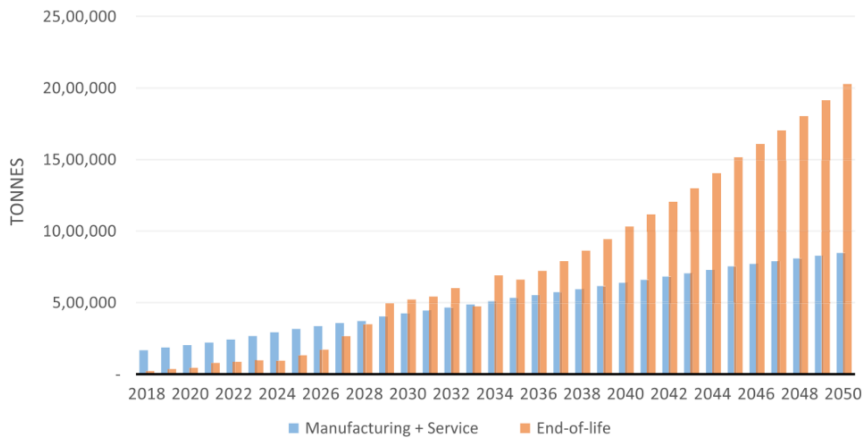

Figure 3 Expected growth of EOL blades (orange) and scrap produced during manufacturing new and service of blades in use (blue)up to 2050 (Liu & Barlow, 2017)

Switching from a linear take-make-use-dispose framework, to a circular one could tackle many problems of this waste stream. In a circular economy the product life cycle consists of (closed) loops which feed back into the resource flow compared to the linear and open 'cycle' of linear economies (Figure 5).

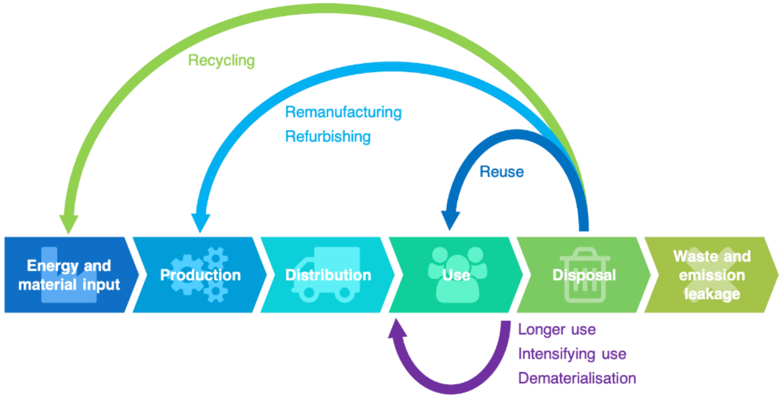

Figure 5 A visual representation of the circular economy framework (Geissdoerfer, Pieroni, Pigosso, & Soufani, 2020)

Joustra, Flipsen and Balkenende (2021) presented five distinct circular strategies which are tailored for products containing composite materials (Table 1). These strategies can also be applied to WTBs.

Circular strategy	Description
Long life	Ensuring long product lifetime by promoting long use and reuse of the product as a whole, through manufacturing physically durable products, resisting aging, fatigue and corrosion, able to sustain wear and tear without failure.
Lifetime extension	Extending the time in use through maintenance, repair, technical upgrading or adapting, by users or service personell.
Product recovery	Returning products or parts to working condition, thereby increasing the numer of use cycles.
Structural reuse	Retrieving structural elements, preserving the material composition, through repurposing, resizing, or reshaping product parts for reuse in another context or construction.
Recycling	Recovery of material through thermal, chemical, or mechanical processes, resulting in raw materials ("recyclate"), aiming to close the materials loop.

Table 1 Circular strategies which can be applied during the design of composite products.

Most existing WTBs are manufactured from glass fibre reinforced thermoset polymers. This class of composite material can resist fatigue damage well and does not corrode which fits the long life circular strategy of Table 1(Majewski, Florin, Jit, & Stewart, 2022). Lifetime extension of the blades is being researched (Ziegler et al., 2018), however the current economic lifetime still ends at around 20-25 years. Product recovery is being implemented with companies selling second-hand blades (Dutchwind, 2021). The extent and maturity of the market for this circular strategy is however unknown (Beauson, Laurent, Rudolph, & Pagh Jensen, 2022). It is the last three of the strategies where the thermoset material becomes a problem because it cannot be easily reshaped or recycled (Majewski et al., 2022). However, even without reshaping, structural re-use applications such as benches or playgrounds keep the material value high by preserving the material composition and exploiting the material's qualities (Joustra, Flipsen, & Balkenende, 2021). Lastly, recycling efforts are increasing but prove financially challenging due to the low virgin glass fibre price (Liu, Meng, & Barlow, 2022). Recycling methods include chemical separation of glass fibers and epoxy, retaining long fibers, and mechanical recycling where the material is shredded, thereby greatly reducing the recyclate value since the fibers are cut (Majewski et al., 2022). Additionally, several heat based methods of separating the matrix from fibers are being explored, aiming to reduce value loss by re-using the fibers and/or the matrix (Hagenbeek et al., 2022). Mechanical recycling is currently the only viable recycling option with about 30% of blade waste ending up as low value filler material (Larsen, 2009). The rest either ends up as landfill or pyrolysis, a process where the material is decomposed by heat in absence of oxygen, where almost no material value is recovered .

The use of thermoplastic composite materials in WTBs, so called TPC WTBs has been an ongoing research topic for more than a decade because, besides possible weight savings, TPCs are easier to recycle than TSCs (Cousins, Suzuki, Murray, Samaniuk, & Stebner, 2019; Joncas, 2010). Research showed that chemical separation of fibers is possible with low energy usage (Cousins et al., 2019). Other research initiatives like the ZEBRA consortium focus on the retrieval of both the fibers and the matrix (Boisgontier, 2022). This consortium also yielded a 62m TPC WTB which can be seen in Figure 6. Because of the thermoplastic matrix, the whole composite can be ground down to a fibrous powder and injection molded where previously only the fibers were targeted for recovery. This makes recyclate from TPC's more valuable that TSC's (Cousins et al., 2019). Even though these material recovery options look promising, they are focused on recycling, breaking up the material composition and lowering its value.

Figure 6 The ZEBRA consortium produced a 62m long blade which can be 100% recycled, retrieving both fibers and matrix material (GE News, n.d.)

By definition thermoplastic composites are thermoformable with derivatives of this process being used to form TPC parts for over 40 years (Offringa, 1996). This ability to alter the shape of TPC's opens up a new possibility in the structural re-use strategy: reshaping. In reuse through reshaping, the arrangement of the fibers and matrix is kept intact which results in minimal loss of value. Contrary to structural reuse through resizing and repurposing, which is dictated by the original products shape, reshaping offers new design freedom. In theory, geometries can be made independent of the shape of the 'host' product (Figure 7).

In their research, Cousins et al. (2019) showcased the feasibility of thermoforming TPC WTB material by straightening a spar cap section. Additionally, a skateboard deck was formed, proving structural re-use by reshaping can create re-use applications of WTB material. However the reshaping efforts in this study only function as an example and limited information is provided about the forming process and performance properties. Furthermore, by making a relatively flat geometry like a skateboard, the ability of the material to be reshaped is not demonstrated to its full potential. No other literature was found discussing re-use by reshaping leaving a knowledge gap. The knowledge gap which will be addressed in this thesis is defined as: a lack of knowledge exists about the characteristics of material retrieved from a TPC WTB and how this is affected by reshaping the material to make it suitable for new applications.

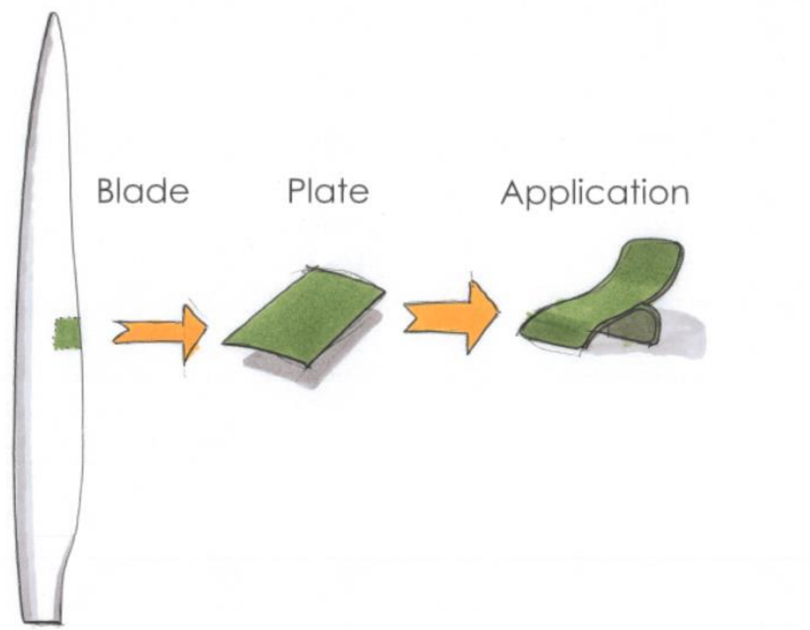

Figure 7 Structural reuse through reshaping showing a curved application can be made of a relatively flat plate originating from a WTB.

1.2 Defining the project

No other literature was found discussing re-use by reshaping leaving a knowledge gap. The knowledge gap which will be addressed in this thesis is defined as: A lack of knowledge exists about the characteristics of material retrieved from a TPC WTB and how this is affected by reshaping the material to make it suitable for new applications.

Besides efforts in attempting to close the identified knowledge gap, I want to draw attention to this currently underexposed circular strategy by making a demonstrator model. This demonstrator can be displayed at fairs and exhibitions, sparking discussions about using reshaped TPC WTB material in reuse applications. Making this demonstrator will also gain valuable insights in the reshaping process.

I formulated the following mission statement for this project:

"Inspiring the industry to develop re-use applications of fibre reinforced thermoplastic wind turbine blades by making a demonstrator product made from reshaped (simulated) wind turbine material."

Research questions

To structure the research performed in this project the following research questions were defined:

To what extent can TPC WTB material be segmented and reshaped and how does reshaping affect its characteristics?

Sub questions:

1. What are the characteristics of a panel retrieved from TPC WTBs?
    a. What are potential segmentation patterns?
    b. What shape can panels retrieved form TPC WTBs have?
    c. What dimensions can panels retrieved from TPC WTBs have?
    d. What is the material composition and structure of panels retrieved from TPC WTBs
    e. What are the material properties of TPC WTB material?
2. How does the TPC WTB material respond to the reshaping process?
    a. What processes can be used to reshape TPC WTB material?
    b. What material defects can arise when reshaping the TPC WTB material?
3. What are opportunities and threats in using TPC WTB panels in re-use applications?

Scope

Due to the lack of literature on the topic of structural reuse through reshaping, many aspects can be explored. Figure 8 shows key aspects in the context of TPC WTBs and shows which are considered out of scope, nice to have, in scope, or belong to the core of this project.

The core elements characterizing the project are:

- Identifying processing parameters in the reshaping process
- The design and manufacturing of a re-use application (demonstrator)

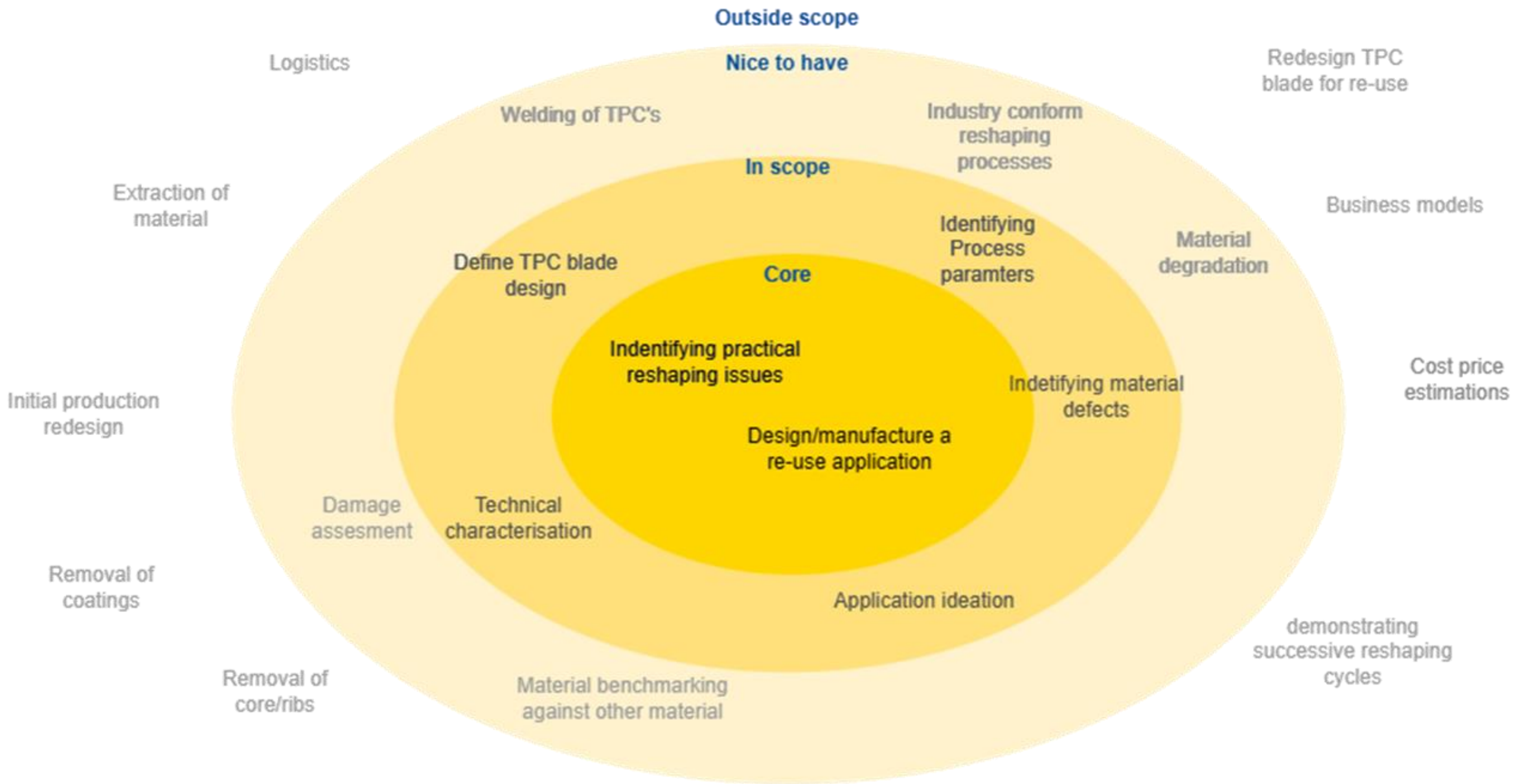

Figure 8 Scope of the project showing elements which are the core, in scope, nice to have or outside the scope of the project

1.3 Method

This project is atypical for a design project as the starting point is a material (with partly unknown properties) for which application areas need to be identified. In this section the general method of the project is explained.

The lack of knowledge makes this project explorative, assumptions have to be made and decision making is complicated because of this. It was therefore decided to use the reflective transformative design process method (RTDP) for this project (Hummels & Frens, 2009).

The RTDP method consist of four elements which each support the central element of Ideation/integrating/realizing. By switching activities a moment of reflection is sparked which helps processing and documenting the knowledge gained during a design activity. This method seems to fit the exploratory nature of this thesis best since no specific order of method is dictated, facilitating iteration while still guiding the process. This flexibility proves for instance useful when insights in the material forming methods leads to design considerations which in term lead to new material forming activities.

Figure 9 shows a schematic representation of how the RTDP method is used for the most important elements in this project. The colors match where these activities can be found in this thesis.

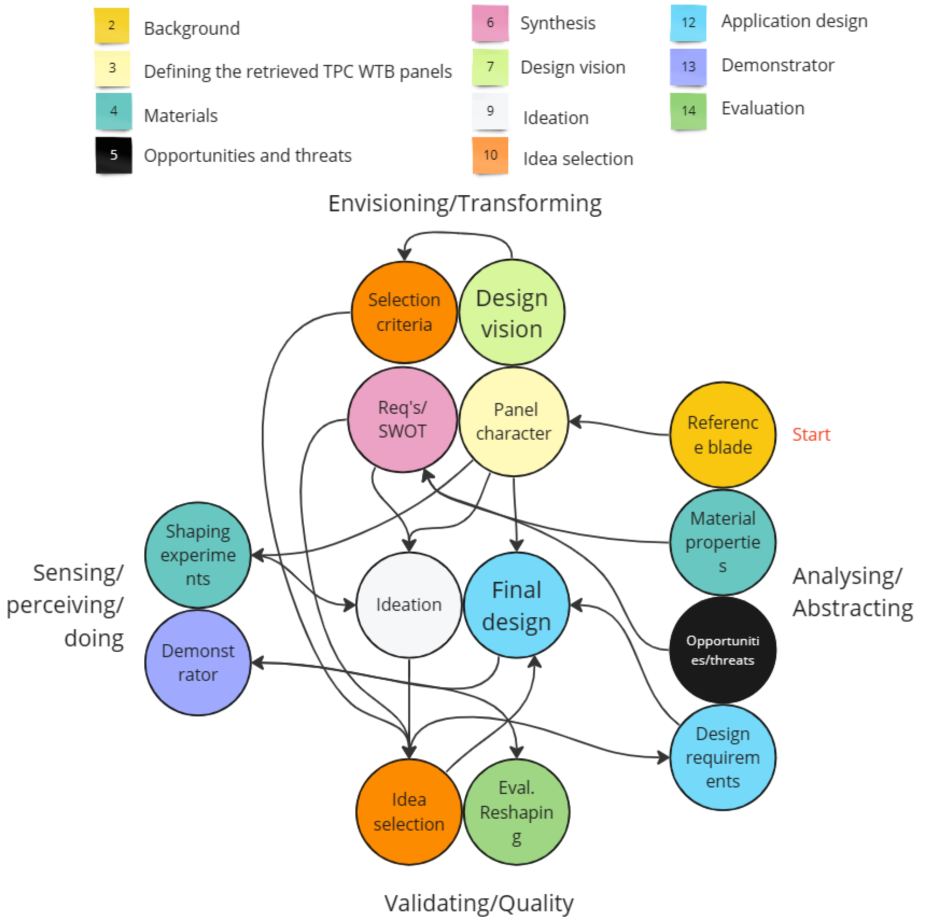

Figure 9 An adapted visual of the RTDP method showing the flow of the most important elements of this thesis. Colour coding corresponds to the chapter in which the elements can be found

2. Background

2.1 Introduction to composites

Composites are an interesting class of materials which combine separate materials to form a new material with enhanced properties. These properties can be tailored by changing the materials in the composite or by changing the structure in which these materials are combined. In this thesis, composites are defined as fibre reinforced polymers (FRPs).

This specific group of composites are composed of two main components, the reinforcement fibers, and the matrix material forming a layer of composite material or 'ply' (Figure 10). When these plies are stacked a so called laminate is made. By changing the structure and orientation of the fibers in the laminate, mechanical properties can be altered in separate directions making the material behave anisotropic. This anisotropy can be exploited to form lightweight structures. The 'layup' scheme shows the different orientation of the fibers inside the laminate.

The reinforcement fibers can be made from a variety of materials such as glass, carbon, aramid and flax. The matrix material is either a thermoset or a thermoplastic polymer. For WTB material, glass fibers in combination with epoxy resin is the standard. For most load cases, the fibers take up the bulk of the load in the direction of the fiber while the matrix provides stability.

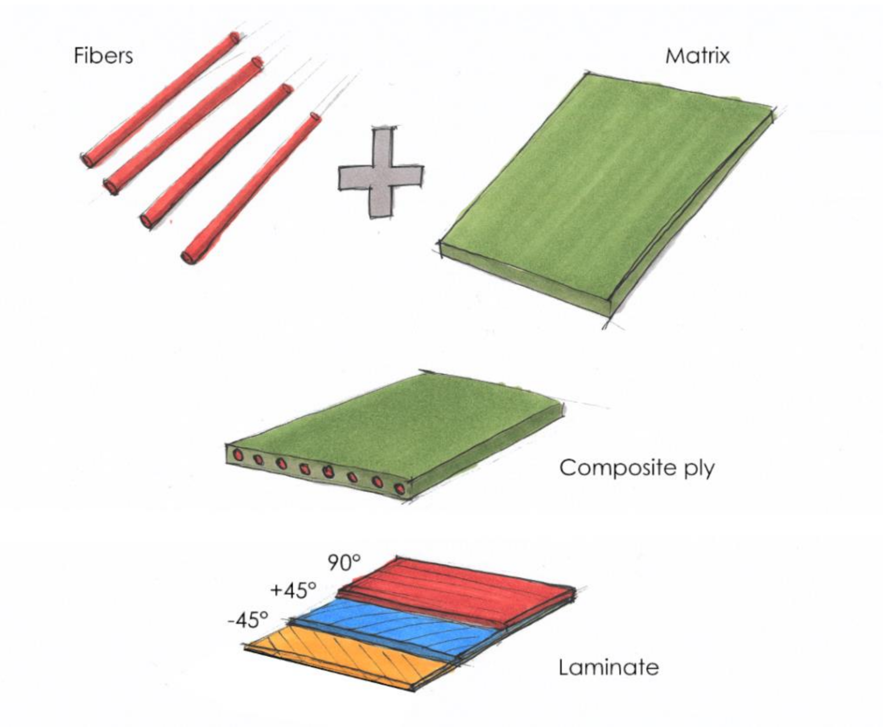

Figure 10 Visual showing the combination of fibers and matrix forms a composite ply and that the plies forms a laminate

2.2 Reference blade

The aim of this chapter is to explore and define what a TPC WTB could potentially look like. The reference blade is based on the 75m blade used by Joncas in his PhD thesis 'thermoplastic composite wind turbine blades' because this was the most comprehensive design report available of a TPC WTB (Joncas, 2010). The scope of this thesis did not entail more detailed design aspects like the exact fabrics used. To define these aspects, other literature and sometimes expert opinion are used as reference.

First, design geometries are defined which later dictate retrieved panel size and shape. The production process is then discussed which is important for making representative layups in the research section of this report. Even more important for research is defining the materials and their structure: the layup. Lastly, a CAD model is presented which incorporates the design geometries found.

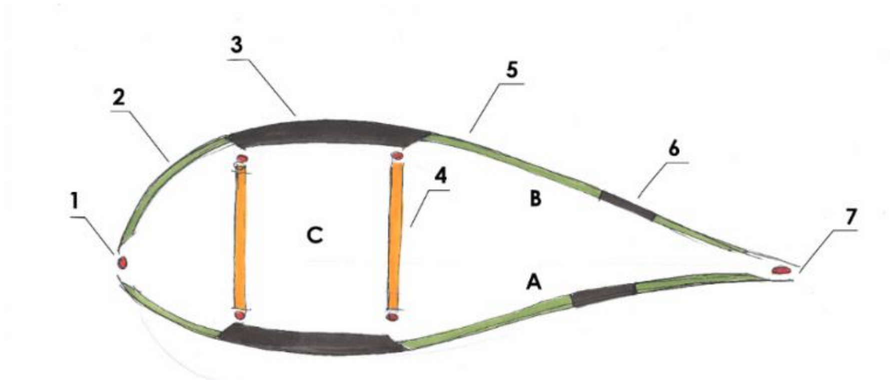

Figure 11 Cross sectional view of a WTB showing the aerodynamic shells A and B and shear webs C. The shells consist consist of a leading edge panel (2), spar cap (3), trailing edge panel (5) and edge wise stiffeners (6). Two bond lines (1&&) are present in leading and trailing edge

2.2.1 Design geometry

Most WTBs consist of three basic parts which can be seen in Figure 11: two aerodynamic shells, one on the suction (top) side and one on the pressure (bottom) side and one or two the shear webs. The shells leading and trailing edge panel as well as the shear webs are of a sandwich construction dropping to a monolithic structure in the leading and trailing edge. The spar cap is a thick monolithic structure taking up the majority of bending loads. These parts are also found in the TPC WTB presented by Joncas. An important side effect of using the two shell method is that a so called bond line is formed at the inside of the leading edge (Figure 12).

Figure 12 Cross section of a WTB showing the leading edge bond line forming adhesive piles.

Due to processing opportunities such as welding, ribs are incorporated which lower the shell thickness and reduce weight. Joncas describes that for his research, 35 ribs were optimal which corresponds to a spacing of approximately 2m for the 75m blade (Joncas, 2010). The shape of the ribs is not known but from topology optimization results it can be seen that the ribs are more stiffeners on the shells rather than airfoil shaped plate like panels (Figure 14).

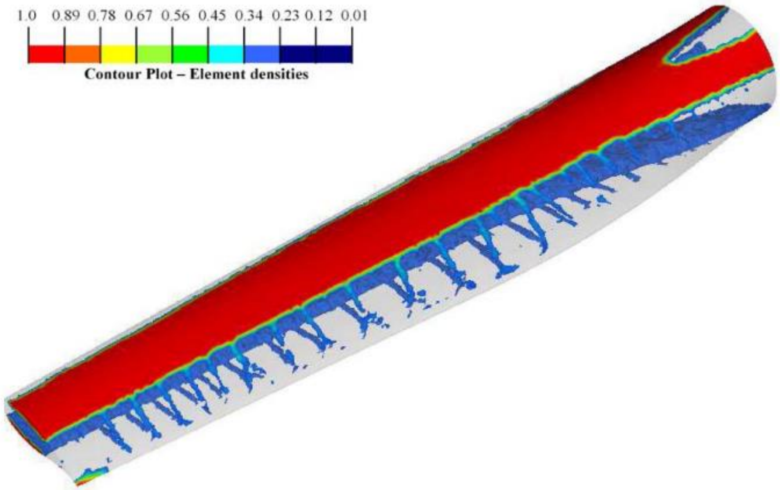

Figure 14 Design optimization of a TPC WTB design study showing ribs (Joncas, 2010)

The aerodynamic shape of a TPC WTB does not differ from regular TSC WTBs. Joncas presents airfoils, their angle of incidence, chord length and spanwise location for his reference blade. This thesis uses this data to construct a CAD model which proved valuable during the blade segmentation in 3.2.1 Segmentation pattern. In this CAD model also the ribs were incorporated. The aerodynamic shape was visually checked by LM Wind Power as to assure that curvatures are representative for an actual blade design. Figure 13 shows a rendering of the CAD model.

Figure 13 Rendering of CAD model made from information found in the doctoral thesis of S. Joncas,

Takeaway

Reference TPC WTB design contains ribs roughly every 2m. This might dictate the retrieved material maximum size.

The ribs in the blade do not contain much material which makes them less interesting to reshape than the shells which contain more material.

A bond line is present in the leading and trailing edge of the blade which can be considered unusable for reshaping re-use applications.

2.2.2 Production process

As discussed in 2.1 Introduction to composites, fibre reinforced composites are made of two materials, the fibers and the matrix. Many processes exist to combine these two materials. Although other options were discussed, Joncas concludes that resin infusion is the most likely production process used for TPC WTBs. Figure 15 shows a schematic of the process where a liquid form of matrix material is drawn through the fibre mats via a pressure difference (P0>P1), created by a vacuum pump.

Takeaway

Similar to conventional WTBs, TPC WTBs will likely use vacuum infusion as the main production process. This process should ideally be used to make representative layups for reshaping experiments.

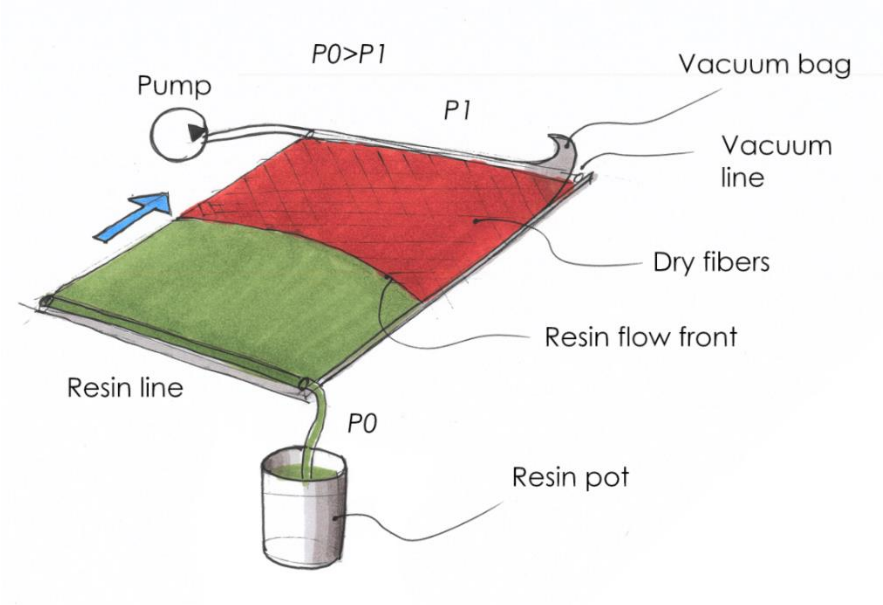

Figure 15 Basics of the resin infusion process where wetting of the fibers is achieved by applying a vacuum on the dry fibers and drawing in resin from a pot.

2.2.3 Materials

Matrices

Vacuum infusion calls for liquid forms of the thermoplastics. This can either be done by melting the thermoplastic before infusion or using a 'reactive thermoplastic'. In reactive thermoplastics, the polymerization takes place during a process which is named 'in-situ polymerization'. These systems typically have a very low viscosity compared to molten, non-reactive thermoplastics making them ideal for the infusion process and as such were selected (Joncas, 2010).

Joncas selected anionic polyamide 6 (PA-6) as matrix material.

Reinforcements

Current WTBs are mainly manufactured from glass fibre reinforced plastics. Glass fibre is a relatively inexpensive material with good mechanical properties making it ideal to use for large structures such as WTBs. Although much rarer, carbon fibres have also been used, mainly in the spar caps. Stiffness is of great importance in this structure, especially when material boundaries are pushed with the ever increasing blade lengths. Joncas chose to use glass fibers only in his reference blade.

For his reference blade, Joncas described two different layers of fiber orientation for the shells and shear: 0° and ±45°. The types of fabrics used are however not presented and will be thus discussed below.

Fibers can be woven, stitched and braided in many different shapes and sizes. In literature, Bi-axial and Uni-directional (UD) fabrics as well as Tri-axial were found to be used in TPC WTB Design (Murray et al., 2021, 2017) was found. This was confirmed by J. Teuwen and S. Jansma (Teuwen, Jansma; 2023) These so called 'non crimp' fabrics are stacks of UD fibers stabilized by a stitching pattern where each layer can have different orientation. Uni, Bi and Tri axial represent one, two and three orientations of UD layers exist in one fabric respectively (Figure 16)

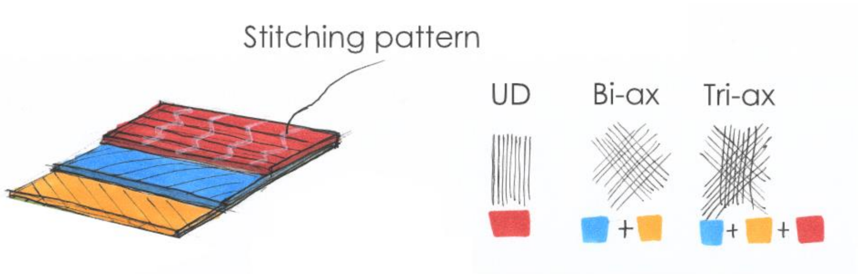

Figure 16 UD, bi-axial and tri-axial non crimp fabrics

The areal weight or grams per square meter is the industry standard to express the thickness of one layer of fabric, also called a 'ply'. Using heavy fabrics, the amount of plies needed is limited, saving on production time and thereby costs. According to J. Teuwen, the bi-axial material used in WTBs is around 800 g/m^2 (Teuwen, 2022). The UD material used is about 1000 g/m^2 according to S. Jansma (Jansma, 2022). Table 2 combines fibre and fabric type and the orientation which can be present in the blade as well as the orientations.

Fibre type	Fibre orientation	Fabric type	
E-Glass	±45°	Bi-ax (>800g/m²)	Tri-ax
E-Glass	0°	UD (>1000g/m²)	

Table 2 Either a Bi-axial+UD or Tri-axial fabrics are used containing the same fibre orientations

Core material

As described in 2.2 Reference blade, most structures in the WTB are made of a sandwich type construction (Figure 17). The mid span section of the wing, PVC, SAN or PET foams are most widely used (Raj, 2012). Both Arkema and LM Wind Power advised to use a (recycled) PET core. The main reason being EOL considerations at the cost of some weight increase and brittleness (Raj, 2012).

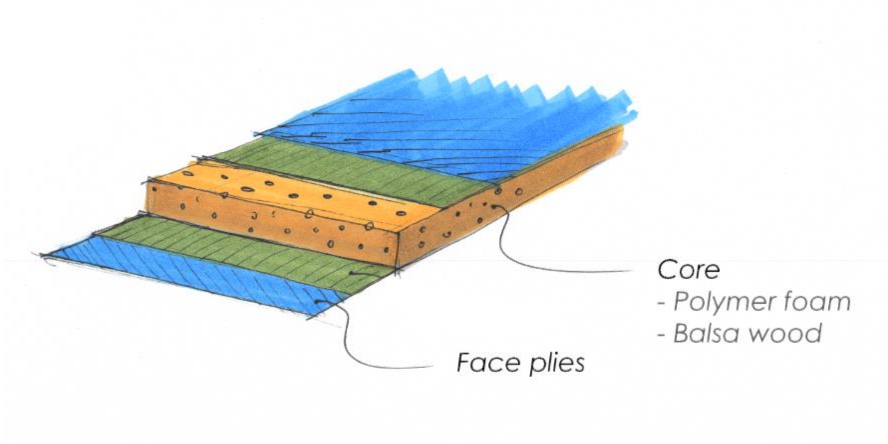

Figure 17 Between the layers of fibre reinforced polymer, the face plies, a layer of core material is placed.

2.2.4 Layups and thicknesses

This section answers research question 1c: What lay-up schemes are used in TPC WTBs?

As described in 2.1 Introduction to composites the layup scheme of a composite represents the stacking sequence, fibre orientation, and if present, which layer is the core material. Combined with the thickness per layer, the layup scheme governs the thickness of the total ply stack. Joncas presents data on percentage UD, the orientation of fibers and thicknesses for face ply and core for the 30-45m section. This however is enough for the purposes of this thesis as a representative panel for reshaping can be chosen within this range. Table 3 provides the orientation of fibers, single face ply/core/total thickness and the percentage UD fibers, for each section of the blade ranging from 30-45m. Figure 18 shows the typical layup scheme of most panels.

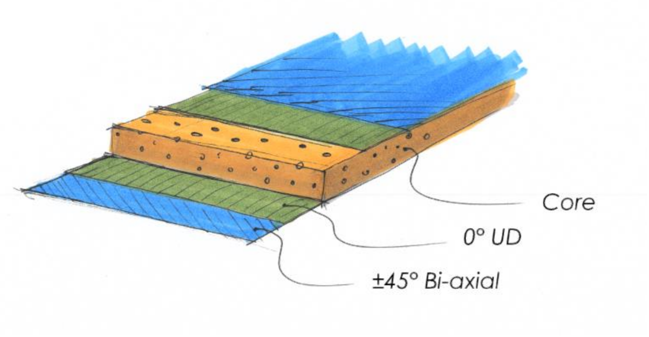

Figure 18 The layup of the reference blade's shell and shear web layup

It should be noted that the presented thicknesses are the result of a design optimization for strength, stiffness and buckling in operational conditions. No manufacturing constraints or other practical constraints were incorporated which could increase the thickness of the plies L.C. Forcier (Forcier, 2022). Furthermore, he values given are based on a PA-6 matrix which means that more exact figures should be re-calculated for an Elium matrix. For this thesis, the purpose of the table is to check if representable laminates are manufactured for reshaping experiments and if so, the origin's location on the blade. When fibre angles are stated, 0° is the spanwise direction.

	location	Fibre orientation	Face ply (mm)	% UD	Core (mm)	Total (mm)
Leading edge	Suction side leading edge	±45° + 0°	1.3	53	7.1	9.7
	Pressure side leading edge	±45° + 0°	2.3	62.9	7.1	11.6
Trailing edge	Suction side trailing edge	±45° + 0°	1.2	22.7	19.2	21.6
	Pressure side trailing edge	±45° + 0°	0.8	60.8	8.3	9.8
Webs	Leading edge web	±45° + 0°	1.3	57.4	6.9	9.5
	Trailing edge web	±45° + 0°	1.5	65.8	8.8	11.7
Spar caps	Suction side spar cap	0°	88.0	97.3	6.6	94.6
	Pressure side spar cap	0°	84.5	97.3	6.4	90.9

Table 3 Information about material structure of the reference blade combined in a table. Note: thicknesses are only for the 30-45m section of the blade

2.3 Damage

Structural damage such as fibre cracking or delamination will greatly influence the quality of the retrieved panel and therefore the resulting re-use application. I therefore decided to incorporate damage into the reference blade. It is assumed that damage regions remain similar for TPC WTBs compared to conventional TSC WTBs.

The leading edge is most significantly damaged but other parts of the blade can also encounter damage in the form of fatigue to fibers and damage to the matrix being the most common according to J. Teuwen (Teuwen, 2022).

From literature, I Identified four types of WTB damage which are described in more detail in appendix A (Katsaprakakis, Papadakis, & Ntintakis, 2021):

- Lightning strike damage
- Fatigue damage
- Leading edge erosion
- Damage from ice/frost

Leading edge erosion (Figure 19) looks to be most prevalent and will roughly correspond to the strongly curved area between and around the leading edge bond lines (Figure 19) for the outer most 28% of the blade length (Verma, Di Noi, Ren, Jiang, & Teuwen, 2021). Aging caused by the cyclic loading is another prevalent type of WTB damage. In TSC WTBs, mostly the root section is affected with defects like matrix cracking and delamination as a result (Katsaprakakis et al., 2021). However no literature was found describing aging effects in TPC WTBs. It is assumed that aging also effects this class of WTBs in the inboard section. Projected on the reference blade, the root section is suspect of fatigue damage where the outer 21m is suspect of leading edge erosion (Figure 19)

Takeaway

Material retrieved from the outer parts of the blade is likely damaged on the leading edge which makes these panels less interesting to use in reuse applications. Aging effects due to cyclic loading and unloading of the blade are not well understood for TPC WTBs but is assumed to only affect the inboard section of the blade

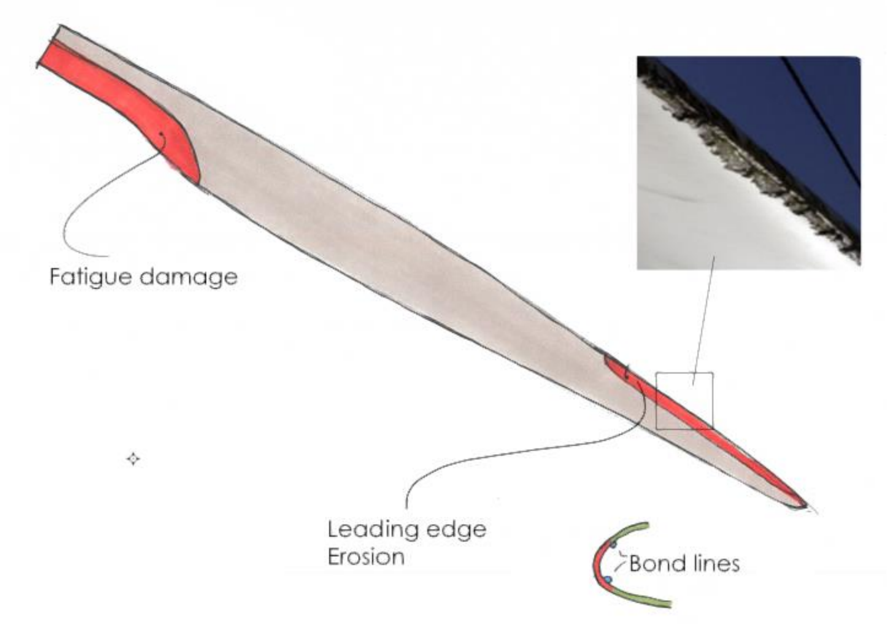

Figure 19 approximate location and extent of damage found on WTBs including a photo of leading edge damage (Katsaprakakis et al., 2021) and overlap of bond line area and leading edge damage

3. Defining the retrieved TPC WTB panels

In this chapter the following sub research questions are answered:

1. What are the characteristics of a panel retrieved from TPC WTBs?
    a. What are potential segmentation patterns?
    b. What shape can panels retrieved form TPC WTBs have?
    c. What dimensions can panels retrieved from TPC WTBs have?
    d. What is the material composition and structure of panels retrieved from TPC WTBs

Figure 20 Mould half of a 115m long WTB (Vestas, 2022)

3.1 Method

The following methods are used to answer the research questions:

1a: What are potential segmentation patterns?

First of all, the segmentation scope of the blade is defined. Following Joustra et al. (2021) a division is made between the inboard, midspan and outboard sections of the reference blade. Because thicknesses, design geometries and material of the inboard and outboard section is missing in this thesis, only the midspan is considered. Figure 21 shows the three sections and their sizes.

The boundaries of the segmentation are based on the following elements:

- Challenging or non-reshapable parts of the blade such as bond lines. Ridges of adhesive in the bond lines of the blade as seen in 2.2.1 Design geometry are hard to reshape and will have a low value in terms of mechanical properties, even if a thermoplastic adhesive is used. Assumed is a 100mm wide bond line for the trailing edge and 50mm bond line for the leading edge. In reality the location of the bond line can vary.
- Leading edge damage found on the blade. Leading edge damage is common in WTBs as described in 2.3 Damage. Panels affected by this damage should be removed as the structural value can be significantly compromised. Fatigue damage could govern a segmentation pattern on its own as well, however it is considered out of scope because the extent and implications of this type of damage is not clear.
- Structural geometries. Because the face ply thickness is in the order of millimeters, it is assumed that removing structures like ribs, will damage most of the plies through thickness. The cross points of ribs, shells and webs result in a segmentation boundary. The thickness of the spar caps could allow the removal of structures like ribs without destroying the structure because only a small percentage of the thickness will be lost due to damaged fibers.

This method of segmentation differs from segmentation patterns based on keeping a constant curvature as found in literature because panels retrieved from a TPC WTB can be reshaped making the curvature less relevant (Joustra, Flipsen, & Balkenende, 2021b). To increase the range of optional re-use applications the segmentation method calls for the panels being as large as possible.

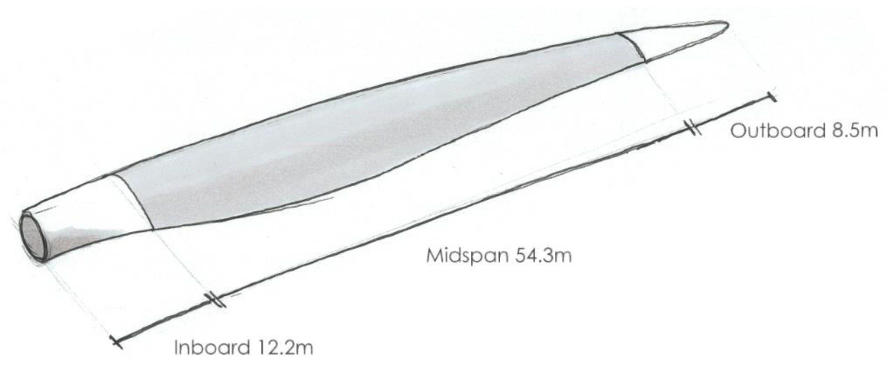

Figure 21 Reference blade divided in inboard, midspan and outboard sections.

1b: Which shapes can retrieved TPC WTB panels have?

1c: Which panel dimensions can be retrieved from TPC WTBs?

Since little material can be retrieved from the ribs these are left out of scope. Shape and size of the retrieved panels are found by projecting the segmentation pattern on the blade. The resulting panels are then classified based on the type of structure: Leading edge, shear web and trailing edge panels (Figure 23). Subclasses are made according to which side of the blade the panel is retrieved from: Pressure ('concave' side) or suction side ('convex' side) for the shear webs and leading and trailing for the shear webs (Figure 23).

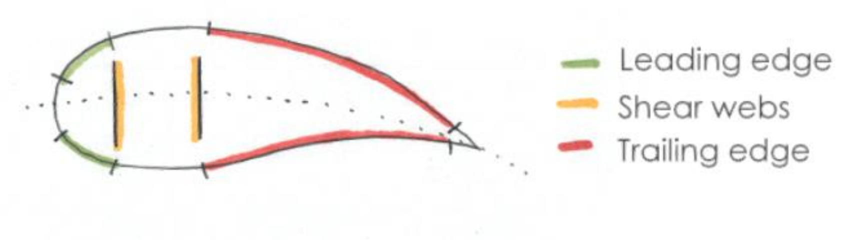

Figure 23 A cross sectional view of a WTB showing the panel classes.

Shape is defined as the outline of a panel from a top view and its curvature. The outline is important as this dictates which re-use application geometry can be made from a single panel or whether multiple panels are needed. The curvature is important to include because highly curved parts could prove difficult to flatten or directly reshape. The radius of curvature was used to define curvature classes Medium (0-2m), Light (3-5m), minute (6-10m) and quasi flat (>11m) based on the most extreme examples found per subclass (Figure 22).

The radius was determined using the following equation: $r = \frac{L^2}{8*h} + \frac{h}{2}$

1d: What is the material composition and structure of panels retrieved from TPC WTBs?

It is important to be aware of the fibre orientation so that it can be optimally taken advantage of in the design of the re-use application. This is also the case for the thicknesses. From 2.2.4 Layups and thicknesses, the fibre orientation and the thicknesses of the reference blade are known and can be integrated in the previously made panel classes.

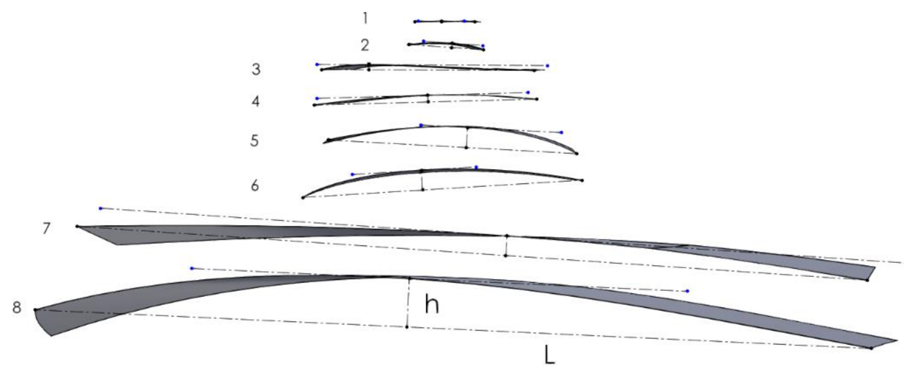

Figure 22 Visual showcasing from every class maximum and minimum curved panels used to make curvature classes. Curvature radius is determined with the chord L and height h of the panels.

3.2 Results

3.2.1 Segmentation pattern

First, the bond lines are removed from the blade which is the first segmentation boundary (Figure 24)

Following the assessed leading edge damage extent of 2.3 Damage, the second segmentation boundary is defined (Figure 24).

The third segmentation boundary is defined by structural geometries. This results in panels limited in width by the spacing of the ribs which is assumed to be 2 meters based on Joncas' proposed and optimized design (Joncas, 2010). The depth (chordwise) of the resulting panels is limited by the spar caps bond lines and the damage segmentation boundary (Figure 24). The width of the segmentation boundary for the spar cap can be much longer than 2 meters and in theory panels of the full blade span can be liberated.

Cutting losses are assumed to be negligible if a water jet is used to liberate material (Joustra et al., 2021b).

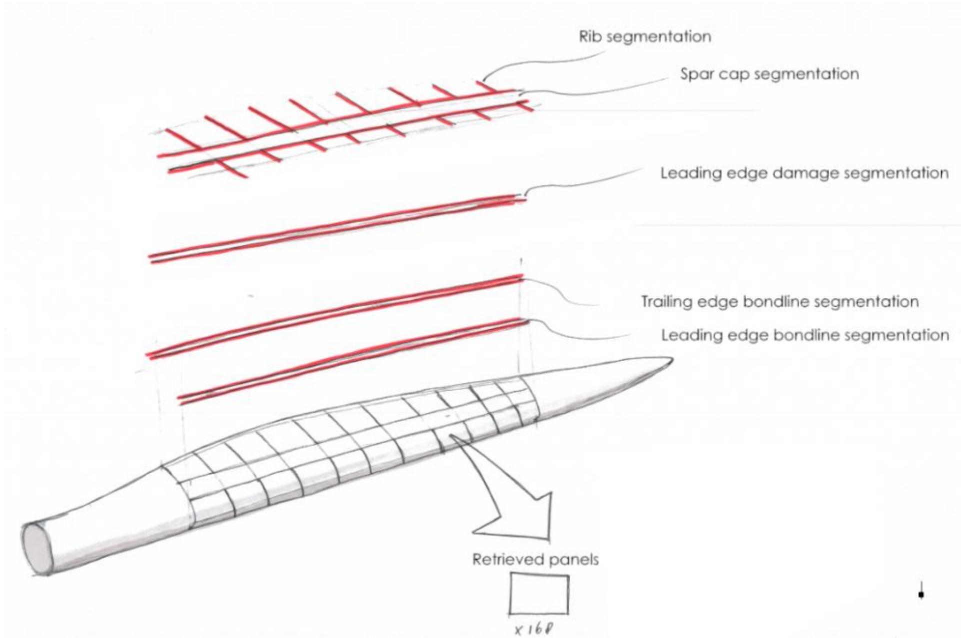

Figure 24 Different segmentation layers and the result projected on the blade surface

Takeaway
Panels retrieved from the shell of the blade have a maximum width of 2m. This can influence the design of re-use applications that require wider panels.

3.2.2 Panel shape, size, fibre orientation and thickness

Projecting the segmentation boundaries onto the reference blade yields 168 panel sections.

The panel outline is trapezoidal as can be seen in Figure 26. The curvature of the plates varies although no extreme curvatures were found because the segmentation boundary of the bond line discards the most curved parts. Table 5 Range of panel radii and the corresponding curvature classprovides the range of radii which make up the curvature classes. These defined curvature classes based on the curvature radius of Medium (0-2m), Light (3-5m), minute (6-10m) and quasi flat (>11m) are presented per panel class in Table 4 Combined results from classification of panels, their size, curvature class, fibre orientation and thicknesses. This table can be used when designing reuse applications. including flat geometries like the shear webs. The arc length which is the depth (chordwise) of the plate when it would be flattened, however varies as the chord length of the blade gets smaller towards the tip. Fibre orientation of the different panel classes was found to be the same. Because only data from the 30-45m section of the reference blade could be found, the full range between the inboard and outboard sections cannot be given.

The results are combined in Table 4. A distinction is made between the largest and smallest extremes per class: respectively inboard and outboard. This distinction is also used for the curvature of the panels since this varies over the span of the blade. Ideally, Table 4 would incorporate data for all panels per class, including the thickness and layup. This would however be out of scope for this thesis. Accompanying the table is a visual showing the pressure and suction sides of the blade along with color coded classes (Figure 25) and a visual showing the maximum and minimum size of the panels (Figure 26).

Although spar caps are not a panel like structure they were incorporated into Table 4 since valuable material could potentially be retrieved. These beam-like structures have no limit on their width, as is discussed in 3.2.1. Furthermore, almost all fibers lay in the spanwise direction making the panel's material properties highly anisotropic which can be exploited in re-use applications.

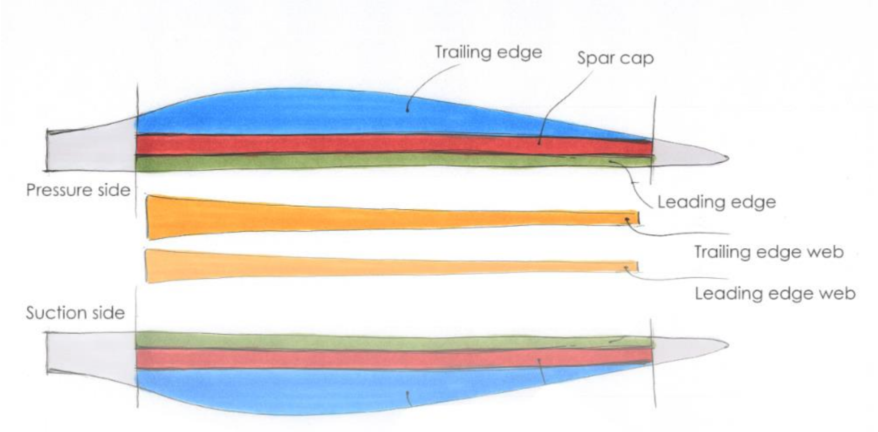

Figure 25 Different classes of panels found in the blade colour coded to fit table 2

Figure 26 Largest and smallest panel found in the blade [Placeholder]

Table 4 Combined results from classification of panels, their size, curvature class, fibre orientation and thicknesses. This table can be used when designing reuse applications.

30-45m (75m Joncas reference blade)

Class	Subclass	Width (m)	Arc Length/depth (m)		Curvature class		Fibre orientation	Total thickness	Core thickness	Face ply thickness
			Inboard	Outboard	Inboard	Outboard	(0°=spanwise)	(mm)	(mm)	(mm)
Leading edge	Suction	2	0.85	0.25	Medium curved	Light curved	[+-45°] Bi-ax + [0°] UD	9.7	7.1	1.3
	Pressure	2	0.9	0.2	Medium curved	quasi flat	[+-45°] Bi-ax + [0°] UD	11.6	7.1	2.3
Trailing edge	Suction	2	2.9	0.65	Light curved	Minute curved	[+-45°] Bi-ax + [0°] UD	21.6	19.2	1.2
	Pressure	2	2.9	0.65	Minute curved	Minute curved	[+-45°] Bi-ax + [0°] UD	9.8	8.3	0.8
Shear webs	Leading	2	1.4	0.2	Flat	Flat	[+-45°] Bi-ax + [0°] UD	9.5	6.9	1.3
	Trailing	2	1.4	0.24	Flat	Flat	[+-45°] Bi-ax + [0°] UD	11.7	8.8	1.5
Spar caps	Suction	-	2.2	0.5	Light curved	Medium curved	[0°] UD	94.6	-	94.6
	Pressure	-	2.2	0.5	Light curved	Medium curved	[0°] UD	90.9	-	90.9

A table like table 2 can be used to match reuse application requirements on size, curvature, layup and thickness with the right panel class

Takeaway

Retrieved panels are not strongly curved which means that large shape differences are needed in the reshaping process when the re-use application is strongly curved. Vice versa, flatter re-use applications require little reshaping. A re-use application that would benefit from an already curved panel can be matched to a specific panel class accordingly.

The thickness of the panels is different per class and changes over the blade length. This means that the required thickness for a re-use application can to a certain extent vary, creating some design freedom.

When flat panels are required for a re-use application these can be retrieved from the shear webs.

Table 5 Range of panel radii and the corresponding curvature class

r (m)	Curvature class
< 2	Medium
3-5	Light
6-10	Minute
>11	Quasi flat

3.2.3 Sandwich and monolithic panels

Reshaping thick sandwich structures will likely be possible. However large bending radii reaching 0.5m are to be expected as consulted with T. Ahmed from Curve works, a company specialized in thermoforming large (sandwich) panels (Ahmed, 2022). Although stiff, strong applications can be designed using sandwich panels, the large minimum bending radii quickly steer potential applications in the direction of large structures. It is also assumed that due to the increased area moment of inertia, significant pressure should be applied during reshaping of sandwich panels.

Separating the face plies from the core would result in thin laminates which can be reshaped with much smaller radii enabling smaller re-use applications.

There are several possible separation methods, of which mechanical separation by peeling the laminate from the core looks most promising (**Error! Reference source not found.**). This method is based on the 'climbing drum peel test' where the relatively weak peeling strength of the laminate is exploited (ASTM, 2021). After separation, it is entirely possible there are pieces of core material left on the laminate and these should be removed Figure 28 A possible method of splitting the relatively thin face plies from the core material can be based on D1781-98 published by ASTM (Figure 28).

Takeaway

Reshaping sandwich panels likely results in big reuse applications.

Separating thin monolithic panels from the core could be an interesting opportunity in reducing minimum curvature radii.

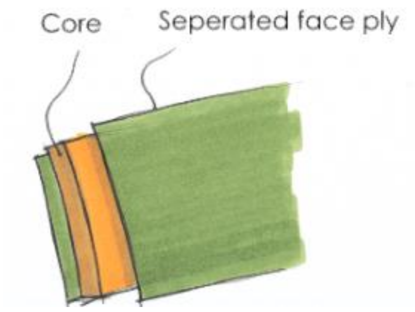

Figure 27 Face plies separated from the core material of sandwich structure

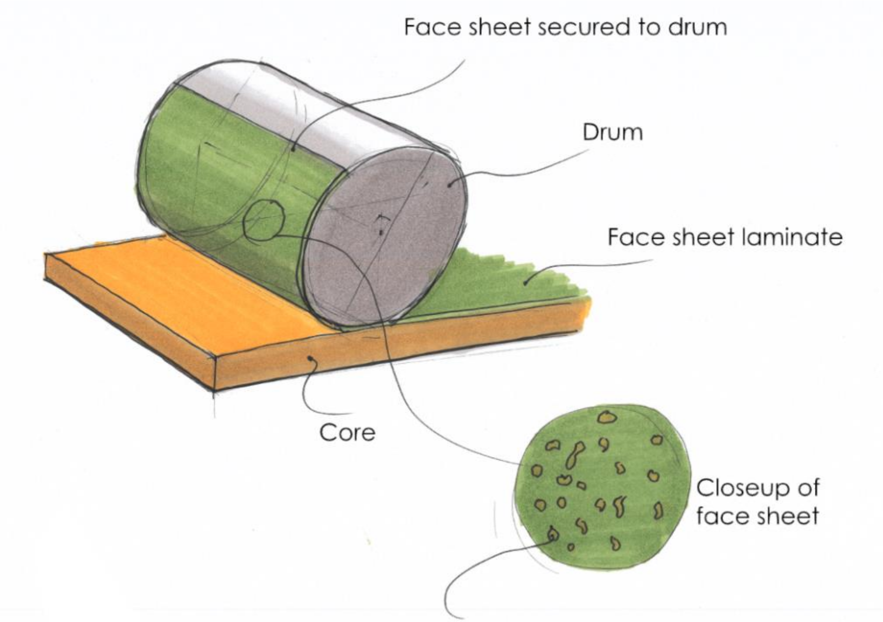

Figure 28 A possible method of splitting the relatively thin face plies from the core material can be based on D1781-98 published by ASTM

3.3 Conclusion

To conclude the research questions are answered and discussed

1a: What are potential segmentation patterns?

A promising segmentation pattern could be the one shown in Figure 24, here, blade damage, bond lines and geometric conditions are all taken into account.

1b: What shape can panels retrieved form TPC WTBs have?

The shape of the retrieved panels is defined by the outline of the shape and its curvature. The outline of the proposed shape is trapezoidal. The curvature of the panels lies between 0.6 (leading edge) and 13.4m (trailing edge).

1c: What dimensions can panels retrieved from TPC WTBs have?

From Table 4 it can be seen that the dimensions of the panels range between 2.0x2.9m and 2.0x0.2m. The biggest panels can be found in the trailing edge close to the inboard section of the blade. This means that bigger applications likely need to source closer to the inboard section while smaller applications can be sourced towards the tip of the blade.

1d: What is the material composition and structure of panels retrieved from TPC WTBs?

In Table 4 it can be seen that the fibre orientation is constant for all panels except for the spar caps. The spar caps have a pure unidirectional layup making them ideal for structures that have a predictable load path such as pure bending along the fibre direction. The other panels can be used in applications where load paths are less predictable or several loading directions exists such as bending coupled to torsion. The thickness was only found for the 30-45m section so the question cannot be answered for all panels. However the presented thicknesses do provide an insight in the difference in thickness between each panel class.

Because making large structures, which is a likely result from reshaping thick sandwich structures, is impractical within the limited time scope of this project I decided to continue with monolithic panels. Reshaping thin laminates likely results in smaller applications.

A assumption is made that face plies can be successfully separated from the core, resulting in monolithic panels.

4. Materials

In chapter 3 shape size, material composition and structure of the retrieved panels are defined. To be able to design with this material, the capabilities and performance in terms of reshaping limitations, material properties, and external opportunities and threats should also be known.

In this chapter the following research questions are answered:

1. What are the characteristics of a panel originating from TPC WTBs?
    e. What are the material properties of TPC WTB material?
2. How does the TPC WTB material respond to the reshaping process?
    a. What processes can be used to reshape TPC WTB material?
    b. What material defects can arise when reshaping the TPC WTB material?

First, an exact material selection is presented together with the process of making laminates in section 4.1. In 4.1 these laminates are then shaped, to explore the reshaping process and material defects (Figure 29). Then, material properties are presented followed by some non-shaping experiments in 4.3 and 4.4.

Figure 29 Composition of material tinkering activities samples

4.1 Simulated WTB laminates

To get material experiment results which are as realistic as possible, representative laminates which simulate the material retrieved from a WTB have to be made. To make these layups, first, the exact materials are selected based on the reference blade and are changed where necessary. Then the production process of the WTB is mimicked, taking curvature into account.

Table 6, also found in 2.2.4 Layups and thicknesses, shows the fibre and fabric type and the orientations which can be found in the skin and shear webs of the reference blade.

Fibre type	Fibre orientation	Fabric type	
E-Glass	±45°	Bi-ax (>800g/m²)	Tri-ax
E-Glass	0°	UD (>1000g/m²)	

Table 6 Two options for layup of the simulated laminates exist Bi-axial+UD or Tri-Axial

810g/m² bi-axial material (Saertex X-E-810 g/m²) was found at the faculty of Aerospace Engineering of the Delft University of Technology. I therefore chose to opt for the Bi-axial + UD layup option. Finding over 1000g/m² proved difficult however since this is quite a niche fabric type. Instead, 600g/m² UD 'tape' was used to manufacture laminates (Polyservice UD tape 7,5 CM 600 g/m²). The fabric's weight however is important. Wolthuizen, Schuurman and Akkerman described that the most common material defects in shaping TPC's during initial production are dependent on deformation mechanisms such as intra ply shearing and ply-ply slippage (Wolthuizen, Schuurman, & Akkerman, 2014) (Figure 30). Both are dependent on the type and weight of the fabric in the layup. Ply- Both are dependent on the type and weight of the fabric in the layup. Ply-ply shearing is depending on the amount of ply-ply interfaces, and thus fibre weight, whereas intra ply shearing is dependent on the weaving of the fabric. It becomes apparent that the areal weight and weaving/stitching pattern is likely an important factor in the re-shaping process. Switching from 1000g/m² fabric to 600g/m² tape thus likely influences results in reshaping efforts. Table 7 shows the implications of this switch.

Changes due to stwitching from 1000g/m² fabric to 600g/m² tape	Implication to research results
Weaker, less stiff laminate	Not a problem since the aim of the research is not to asses the strenght/stiffniss of the material
Change in buckling behaviour due to decreased thickness	Not a problem since it is speculated that likeliness of fibre buckling is incrreased therefore reshaping efforts show a worst case scenario
local thickness in or de-crease in laminate as tape layers may overlap or seperate	Can pose a problem since local changes in laminate thickness can facilitate material defects
Improved ply-ply slippage as tape lines can slip without having to shear	Can pose a problem as falsely positive shaping results are presented
Improved intra ply shear as tape material can more easily shear in-plane	Can pose a problem as falsely positive shaping results are presented

Table 7 Changes in the laminate and the implications to the research by switching from>1000g/m² fabric to 600g/m² tape material in the simulated laminates.

Based on the research of Wolthuizen, Schuurman and Akkerman (2014), I argue that the number of plies is more important than the actual thickness of the laminate and that reshaping results are still valuable even though the results might a false positive. The effect of stitching patterns on forming limits is not known and should be addressed in further research.

In the reference blade the matrix material is defined as anionic PA-6. However, the polymerization initiation temperature lies between 170-180°C which complicates requirements for moulds and other items used during production of the laminates (Joncas, 2010). To avoid complications due to temperature resistance of materials used in production another matrix material was selected. Three sources were found using Elium which is the brand name of a type of PMMA from Arkema to manufacture TPC WTB's (Boisgontier, 2022; Murray et al., 2021, 2017). By adding 2-3% by weight peroxide powder (BPO), the polymerization process is started to form polymethylmethacrylate (PMMA) (Arkema, 2022). This polymerization reaction takes place at room temperature. Because of the room temperature curing and the fact that it has already been used to build a full scale wind turbine blade by LM Windpower (Boisgontier, 2022), Elium was chosen as the matrix material.

The production process of the laminates is similar to that of the reference WTB in that it is manufactured by means of vacuum assisted resin infusion (VARI), commonly known as vacuum infusion. This technique is explained in Chapter 2.2.2. Figure 32 shows the cross sectional stack of materials used in infusion.

The resulting laminates using the specified fabrics are between 1.1 and 1.2mm thick. The amount of UD is about 43% in the laminates. By using Table 4 presented in chapter 3.2.2 the simulated location of the manufactured panel can be found. Suction side leading edge, pressure side trailing edge or leading edge web class for the 30-45m section are within 0.1-0.2mm of the manufactured and are thus most likely. I chose to opt for the leading edge because I assumed that the increase in curvature might create unforeseen problems in the forming experiments which would create valuable insights. Figure 31 shows the setup of an infusion on a WTB section which roughly matched curvatures for 30-45m section in the CAD model of the reference blade.

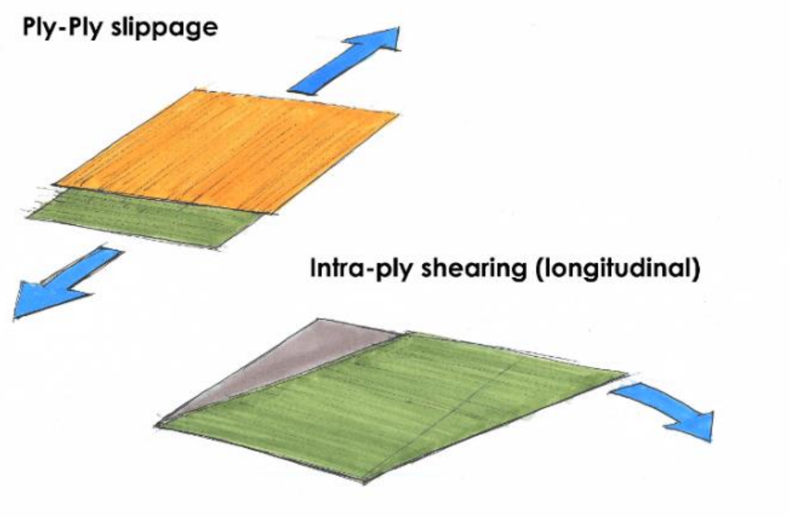

Figure 30 Ply-Ply slippage and Intra-ply shearing are identified as important deformation mechanisms in shaping TPCs

Takeaway
The manufactured laminates are not fully representative for the reference blade but are believed to produce valuable insights

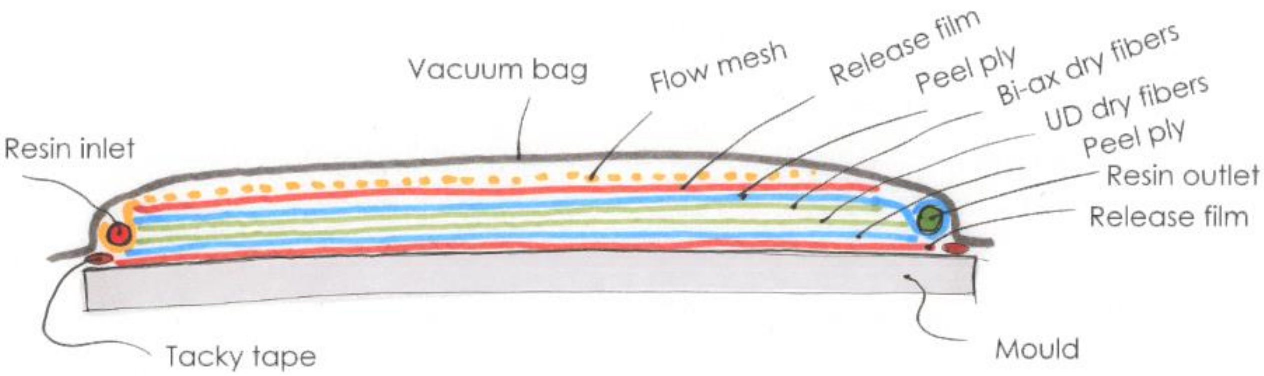

Figure 31 Infusion setup to manufacture curved laminates

Figure 32 Cross section of an infusion setup [Placeholder]

4.2 Re-shaping experiments

In this subchapter the following research questions are answered:

2. How does the TPC WTB material respond to the reshaping process?

    c. What processes can be used to reshape TPC WTB material?

    d. What material defects can arise when reshaping the TPC WTB material?

Each experiment has a more specified goal which can be found in Table 8. This table also shows the layup and thickness of the shaped panel of each test. Appendix B to E give a more detailed account of the process and results per experiment.

Method

For all reshaping experiments, thermoforming was used where the laminate is heated to temperatures above Tg ranging between 140-180 °C after which pressure is applied to make the laminate conform to the chosen mould shape. The initial reshaping method of thermoforming with temperatures of 180 °C was chosen because Arkema recommended this temperature (Arkema, 2017). In all experiments but the first, pressure was released after the part cooled down significantly below the Tg of 115°C to avoid spring back and/or excessive internal stresses. Apart from this general method a distinction can be made on process parameters such as how the pressure is applied, reshaping temperature and mould shape. The set of process parameters for each experiment can be seen in Table 8. Although matched die forming would be more representative of a method used in the TPC forming industry, the vacuum bag method was used because this is much less time consuming and more feasible in the context of this project (Michael C.Y. Niu, 2000).

Table 8 Overview of the five reshaping experiments and where the laminates and process parameters differed

			Laminate		Process paramaters							
#	Title	Goal	Layup	thickness (mm)	Method	Applying heat	Reshaping temp (°C)	Reshaping pressure (mBar)	Time above Tg (minutes)	Mould shape	Radii (mm)	
1	Initial formimg test	Assesing if the produced glass/elium panels are shapeable	2x 812g/m^2 bi-axial [+-45°] of length axis mould	1.2	Hand shaping	Convexion	Unknown	Unknown	Seconds	Conical	Max	Min
2	Vacuum bag forming	Controlling parameters; reduce defects	2x 812g/m^2 bi-axial [+-45°] of length axis mould	1.2	Vacuum bag forming	Convexion	180-190	54-75	60	Conical	40	24
3	Corrugated sheet	Idea validation; shortening temp. exposure time to reduce browning	2x 812g/m^2 bi-axial [+-45°] of length axis mould	1.2	Vacuum bag forming	Convexion	165-180	Step 1: 600, step 2: 6	35	Wave	±20	±20
4	Dome shape	Asses forming doube curved surface (process and material)	812g/m^2 bi-axial [+-45°] + 600g/m^2 UD of length axis mould	1.1	Vacuum bag forming	Convexion	165-180	85-120	30	Dome	125	125
5	Tube rolling	Idea, geometery and process validation; lowering temperature to reduce browning	812g/m^2 bi-axial [+-45°] + 600g/m^2 UD of length axis mould	1.1	Laminate rolling'	Convexion/conduction	140-160	Unknown	5	Tube	30	30

Results

In this paragraph the results of the shaping tests are presented. A distinction is made between fibre/matrix defects, shape conformity and browning of the matrix. Table 9 combines the results and also lists the insights gained per experiment.

Suspected fibre buckling, sometimes resulting in kink bands was the most prevalent fibre defect found, especially in unsupported areas where the fibers are allowed to move out of plane (Figure 38). Fibre waviness, an in-plane curvature of fibers, was identified also on supported areas where the laminate is pressed between mould and vacuum bag (Figure 37). Both fibre buckling and waviness are signaled by a white area. In areas where bridging occurred, white stripes can be seen (Figure 33). The tube shape showed a large amount of white speckles, reminiscent of the white speckles found on the degradation experiments which can be seen in Figure 35 compared to the tube (Figure 34).

Apart from the double curved experiment, vacuum bag formed parts conform well to the mould shape. However, concave geometries formed with a vacuum bag resulted in bridging. The tube geometry made by rolling the laminate around a tubular mould also showed good shape conformity leaving little room between mould surface and the laminate, resulting in an almost circular cross section (Figure 36). The laminate reshaped into a double curved surface in experiment 4 did not conform to the mold shape showing heavy wrinkling.

Browning occurred in shaping experiments where temperatures reached above 160°C for longer exposure times. At the same time minimal browning occurred below 160°C or short exposure times to temperatures above 160°C.

Figure 38 Fibre buckling on experiment 2

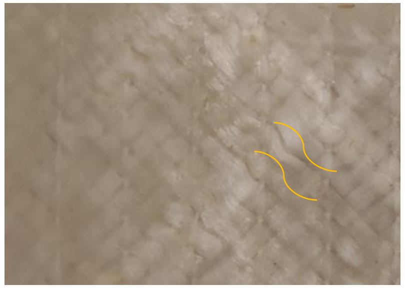

Figure 37 Fibre waviness on experiment 2

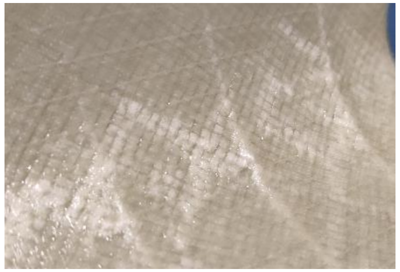

Figure 33 bridging a concave mould feature results in white stripes forming on experiment 2

Figure 36 Cross section of shaping experiment 5 approaching a circle

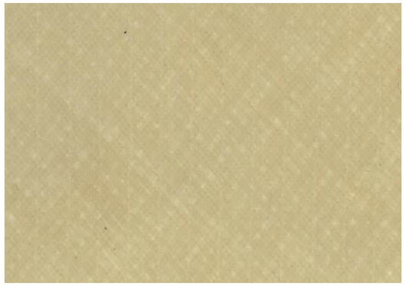

Figure 35 White 'speckles' formed on a non-reshaped but heated panel

Figure 34 Similar white speckles to Figure 35 can be seen on experiment 5

Figure 39 The result after shaping experiments. From left to right: shaping experiment 1, 2, 3, 4 and 5. Notice the difference in browning.

Table 9 Results of the shaping experiments together with insights gained.

		Results			
#	**Title**	**Browning**	**Shape conformity**	**Fibre/matrix defects**	**Insights**
1	Initial forming test	no	Mediocre (no smooth surface)	Kink bands, fibre muckling, fibre waviness. Dry spots	Defect areas are signalled by bright white areas. Reshaping time could be a process parameter. A more controlled process is neeeded.
2	Vacuum bag forming	Yes	Decent (bridging concave parts)	Fibre buckling, kink bands, fibre waviness, dry fibers	Pressure should be released after cooling below Tg. Browning of Elium. Vacuum bag forming creates less defects. Try lowering time above Tg to avoid browning. Defects occur in unsupported areas.
3	Corrugated sheet	Yes	Good (minor bridging concave parts)	Dry fibers	Lowering time above Tg did not impact browing. Corrgated sheet should be manufacturable with the TPC WTB material.
4	Dome shape	Yes	Bad	Heavy wrinkling, fibre buckling, kinkbands,	Radius too small for the process and material. Shallower double curvature should be possible. Forming temperatures can likely be lowered to 150-160°C.
5	Tube rolling	Minor	Good (almost circular cross section)	Dry spots	A 60mm tube should be manufacturable with the TPC WTB material. Lowering the process temperature significantly lessened the browing of Elium.

Takeaway

Re-use applications requiring strong double curved geometries (r=125mm tested) might be challenging to realize without material defects.

Re-use applications using corrugated sheet material are feasible.

Re-use applications using tubular geometries with a diameter not smaller than 60mm are feasible.

In manufacturing the demonstrator, a reshaping temperature lower than 160°C should be aimed for.

4.3 Material properties

In this subchapter research question 1e 'What are the material properties of TPC WTB material?' Is answered.

Method

In researching the mechanical properties, literature research in combination with estimations for strength and stiffness was used. These estimations were made using the Synthesizer tool of Granta EduPack. Appendix G details the estimation process but in short the properties of a UD laminate were retrieved and corrections were made to account for different fiber orientation as this has a strong influence on the properties (Seshaiah & Vijaya Kumar Reddy, 2018). In researching other properties mostly literature research was performed. Weldability was also experimentally verified which can be found in appendix H. Whenever the property of ELIUM could not be found in literature it was assumed that PMMA has similar properties.

Results

Mechanical properties

The brochure of Elium claims that the mechanical properties of Elium based composites are comparable to that of epoxy based composites while specifically the toughness is improved (Arkema, 2017). Chilali et al. show in their research that for GF/Elium composites the tensile modulus, ultimate tensile strength, shear modulus and ultimate shear strength are comparable to GF/epoxy composites (Chilali, Zouari, Assarar, Kebir, & Ayad, 2016). Kazemi et al conclude in their research that the impact resistance and damage tolerance is improved over epoxy based composites (Kazemi et al., 2019).

The strength and stiffness was researched in particular resulting in Table 10. Because I could not find a good rule of thumb to estimate total laminate strength, a range of strengths is given where the largest number is strength in UD direction and smallest in [±45°] direction

Because of the similarity to conventional GF/epoxy laminates, it can be concluded that the specific strength and stiffness of UD GF/Elium laminates are superior to unreinforced polymers or even most metals and some other composite materials. The specific strength and stiffness of Elium is calculated by dividing the strength and stiffness of Table 10 by the density found for UD GF/Elium from Granta's synthesizer which is 1.9E3 kg/m^3. Figure 40 resulting shows a plot of specific strength and stiffness of GF/epoxy and GF/Elium compared to the composite and metal material group. The other groups have, compared to these groups, such low specific strength and weight that they can be found in the bottom left corner.

Mechanical property	E-glass/ Elium
Tensile strength (Mpa)	108-983
Compressive strength (Mpa)	259-809
Youngs modulus (Gpa)	31
Specific Tensile strength (Mpa/kg)	57-517
Specific stiffness (Mpa/kg)	16

Table 10 Estimated mechanical properties of simulated TPC WTB laminate

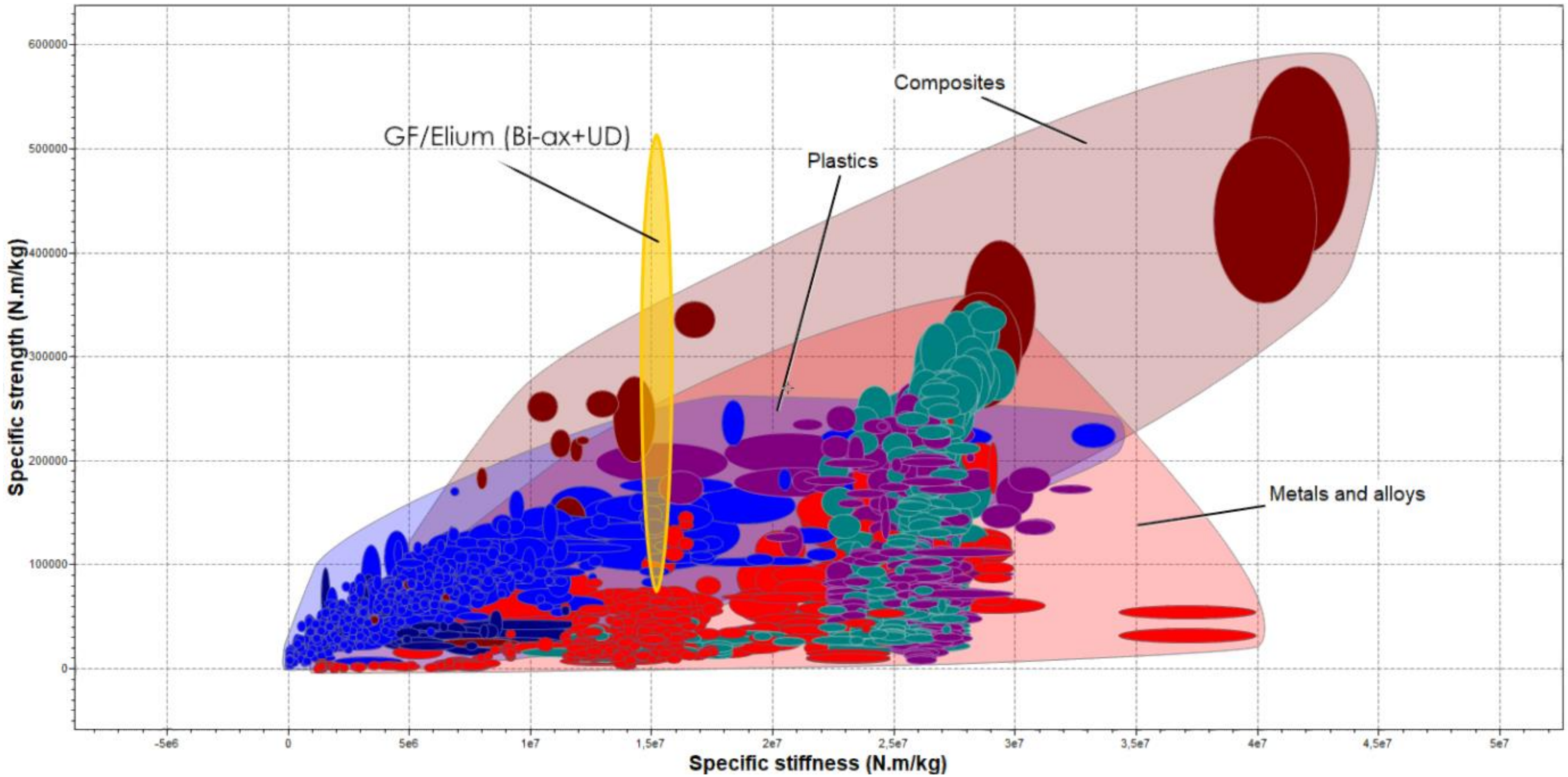

Figure 40 Comparison of specific strength and stiffness between material groups of polymers, metals and composites.

Other properties

The patent on Elium mentions a weak resistance to chemicals (Dana L Swan, Robert A. Wanat, Robert J. Barsotti, Nathan J. BACHMAN, 2019). When compared to conventional PMMA, while being resistant to alkali's, organic solvents and strong acids are detrimental to the material ("Granta EduPack," 2022). When continuously exposed to water, this can lead to degradation of mechanical properties (Chilali, Zouari, Assarar, Kebir, & Ayad, 2018) In the patent of Elium by Arkema it is mentioned that although not as good as regular PMMA, the UV resistance of Elium can be considered good (Dana L Swan, Robert A. Wanat, Robert J. Barsotti, Nathan J. BACHMAN, 2019). As described in the brochure of Elium one of the advantages is weldability (Arkema, 2017). In a lab demonstrator this was also shown according to J. Teuwen (Teuwen, 2022). Glass fibre in itself is not flammable. The matrix however is, when Elium is considered egular PMMA ("Granta EduPack," 2022). Both glass fibre and PMMA are bad electrical conductors making them isolators ("Granta EduPack," 2022) The glass transition temperature of Elium is reported to be around 115°C (Arkema, 2022).

Takeaway
The defined TPC WTB material has the following qualities which can create opportunities or challenges when used in re-use applications:

- More impact resistant then GF/epoxy
- Similar strength/stiffness to epoxy
- Resistance to alkalis, not resistant to strong acids and organic solvents or when exposed for a prolonged time, water.
- Weldable
- UV resistance
- Flammable
- Electric insulator
- It is likely the re-use application requires a protective coating.

4.4 Discussion

The white speckles found on the degradation experiment samples as well as the tube shape, are dry spots according to J. Teuwen (Teuwen, 2023). She hypothesizes that the sizing, a coating around each fibre, is not optimal for the Elium matrix. This leads to insufficiently wetted fibres where the matrix would rather fill the voids between fibre crossings than wetting the fibre bundles themselves. A sketch in Figure 41 visualizes this effect. These insufficient wetted fibres can also be seen in the virgin laminates where the stitching and some fibers cross points form white areas, whereas sufficiently wetted fibers should be un-distinguishable by eye. When heated above matrix melt temperature, the fibers are even more deprived of matrix material. This accentuates the dry spots even more (Figure 42 Comparison of a 'virgin' laminate (left) and heated laminate (right) both showing white speckles at the cross section of fibre bundles). It can be concluded that this type of defect is not caused by the reshaping process because the non-formed but heated plate, experiences the same defect. Re-use applications using tubular shapes with a minimum diameter of 60mm made by the rolling process should therefore be feasible.

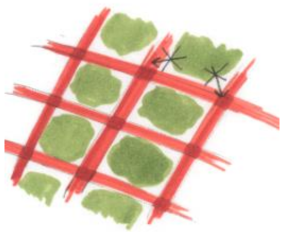

Figure 41 A sketch of matrix material not wetting fibers sufficiently

Figure 42 Comparison of a 'virgin' laminate (left) and heated laminate (right) both showing white speckles at the cross section of fibre bundles

According to J. Teuwen, the browning of the matrix can signal degradation which will negatively influence the material properties (Teuwen, 2023). In literature it was found that most PMMA variations degrade in two steps: between 180-350°C and 250-400°C (Nikolaidis & Achilias, 2018). Because shaping temperatures reached 180°C in experimentation it can be assumed that the browning is indeed the first degradation step. Lower shaping temperatures showed less browning. Appendix F shows that the browning is likely not oxidation.

The bridging found in concave areas is likely a result of low tool-ply slip because the vacuum bag pins down the laminate on the convex parts of the mould (Wolthuizen et al., 2014). This leads to the insight that matched die forming is probably a better process in case concave mould geometries are present. However material defects due to the nature of the material are not found for single curved geometry with a minimum radius of 30 mm. Defects for these geometries are caused by the shaping process.

The vast amount of material defects found in the double curved surface experiment is believed to be a combination of both the material and the process. In literature different results were found using the same mould diameter but different process, matched die forming instead of vacuum bag forming (Wolthuizen et al., 2014). In this research buckling was also present albeit distributed over many much smaller buckling lines. Some areas of the double curved part did not experience material defects which suggests that the right diameter and process can result in positive reshaping results. The implications of the fibre and matrix defects and browning is not well enough understood to discuss its direct effect on re-use applications.

Takeaway

Not all material defects arise from the reshaping process. This should be kept in mind when evaluating the demonstrator.

4.5 Conclusion

From the shaping results the research questions can be answered.

2. How does the TPC WTB material respond to the reshaping process?

The material responds well to reshaping single curved geometries with a minimum radius of 30mm by not showing any shaping induced material defects. However bridging a concave geometry should be avoided as this causes material defects. The material does not respond well to strongly double curved surfaces of r=125mm as the laminate is highly wrinkled after shaping.

2a. What processes can be used to reshape TPC WTB material?

Vacuum bag forming can be used as well as 'laminate rolling'. For parts containing concave geometries matched die forming is likely a more suited process as bridging is avoided. A forming temperature of 150-160°C should be used for this thickness laminates to avoid browning. Also double curved geometries should be made using a form of matched die forming.

2b. What material defects can arise when reshaping the TPC WTB material?

- Dry spots
- Fibre buckling
- Fibre waviness
- Highlighted fibre to matrix interface defects
- Matrix browning

1e. What are the material properties of TPC WTB material?'

This question can be answered with Table 11. To better answer the research question more research should be performed on the properties of the TPC WTB laminates such as mechanical tests.

Material Property	sub category	Result
Mechanical	Shear strength/modulus	Comparable to Glass/epoxy
	Impact resistance	Comparable or better than Glass/epoxy
	Tensile strength	108-983 Mpa
	Compressive strength	259-809 Mpa
	Youngs modulus	31 Gpa
Chemical resistance	Alkali's	good
	Organic solvents	bad
	strong acids	bad
	Water (pronlonged exposure)	bad
UV resistance		good
Flammability		bad
Weldability	ultrasonic	good
Electric conductivity		bad
Glass transition temperature		115°C

Table 11 Material properties found for GF/Elium combined in a table

5. Opportunities and threats

In this chapter research question 3: ‘What are opportunities and threats in using TPC WTB panels in re-use applications?’ is answered.

5.1 Method

From literature research and combining insights gained earlier in the project some opportunities and threats of designing/implementing the TPC WTB material were identified. Also personal experience working with the material was used as a source of information.

5.2 Results

The following opportunities were identified:

1. Experimenting with the material showed that the material can be reshaped as can be seen in chapter 4.2.
2. Currently, in many countries WTB owners must pay a fee for blade disposal (Liu, Meng, & Barlow, 2022). This means the material has a negative value making for a cheap material.
3. If competing with other cheap materials, the likely significantly ‘better’ mechanical properties, will outcompete the cheap material.
4. Competing with other high performance materials can be done based on the low price point
5. A clear opportunity which can be exploited is the growth in popularity of the concept of the circular economy both to consumers and businesses (Demirel & Danisman, 2019)

Next to opportunities also threats are identified:

1. As Polyportis, Mugge and Magnier put it: “The fact that a product is made from recycled materials can decrease consumers, perceived quality of the product” (Polyportis, Mugge, & Magnier, 2022). It is likely that people will regard structural re-use as recycling and by that perceive the quality of the re-use application as inferior.
2. Not every blade has the same geometry or material usage and the supply chain of WTB material for structural re-use is not matured. This creates problems keeping the supply stream volume and composition constant.
3. Not every blade will see the same use cycle resulting in differences in damage and quality of the ‘raw ’material.
4. From personal experience working with cured glass fibre laminates I identified that health hazards are a real threat. Especially if untrained consumers start interacting with the material (i.e. cutting or sanding), without wearing the proper PPE’s health risks can occur.

5.3 Discussion

The price point of the material can be an opportunity as well as a threat. I assumed that in the beginning of re-using the material demand will remain low and therefore the material will be cheap. However when demand rises because the material is implemented in society, the price will likely rise ("What influences raw material prices?," 2022). The extent of the successive life cycle is not yet well understood because factors like aging of the matrix could prevent more than two life cycles. This opportunity must not be seen as a direct environmental sustainable advantage of the material as the impact of the material, especially in re-use applications, is not clear. Another identified opportunity is that of a low (initial) material price point. This claim should however be further investigated. Also the effect on price fluctuations: a threat, should be further investigated. Depending on the outcome of this investigation the opportunities of 'add value over cheap material' and 'substitute expensive material' should be reconsidered. Investigations about the actual quality and consistency of the material are needed. In case the quality of retrieved panels differs depending on the sourcing locations this can form an extra input for the panel classification table presented in chapter 3.2.2 Panel shape, size, fibre orientation and thickness.

5.4 Conclusion

Research question 'What are opportunities and threats in using TPC WTB panels in re-use applications?' can be answered with table 12.

Table 12 The identified opportunities and threats in using TPC WTB material in re-use applications combined in a table.

	Opportunity
1	Multiple life cycles while retaining structure
2	Cheap material
3	Add value over cheap material
4	Substitute expensive material
5	Growth in popularity of the circular economy

	Threats
1	Uncertain material price/Price fluctuation
2	Public quality concerns
3	Supply consitency
4	Quality consistency
5	Health hazards when processing the material

Takeaway

Material price fluctuations can be expected, making the material unsuitable for re-use applications who's success is highly dependent on material price.

Fitting applications might be found when the material is either substituting a high performance material which applications benefits a lower price; or a lower performing material which applications can benefit from a higher performing material.

Re-use applications that are safety critical and therefore need a reassuring material with high perceived quality are not a good fit for the TPC WTB material.

6. Synthesis

Concluding the research phase I synthesized the key findings of chapter 3 and 4 into a SWOT matrix as well as a first set of design requirements.

6.1 SWOT

Most of the research phase can be considered an internal analyses with insights leading to strengths and also weaknesses of the material. The short external analysis unveiled some threats of implementing the material in re-use applications but also opportunities. These finding were combined and structured in SWOT matrix which can be seen in Figure 43.

6.2 Design requirements

Some insights gained in the research phase directly lead to requirements for the demonstrator model and can be seen in Table 13. These will be used in the design phase together with requirements derived from insights gained in the design phase. This more complete set is discussed in Chapter 10.

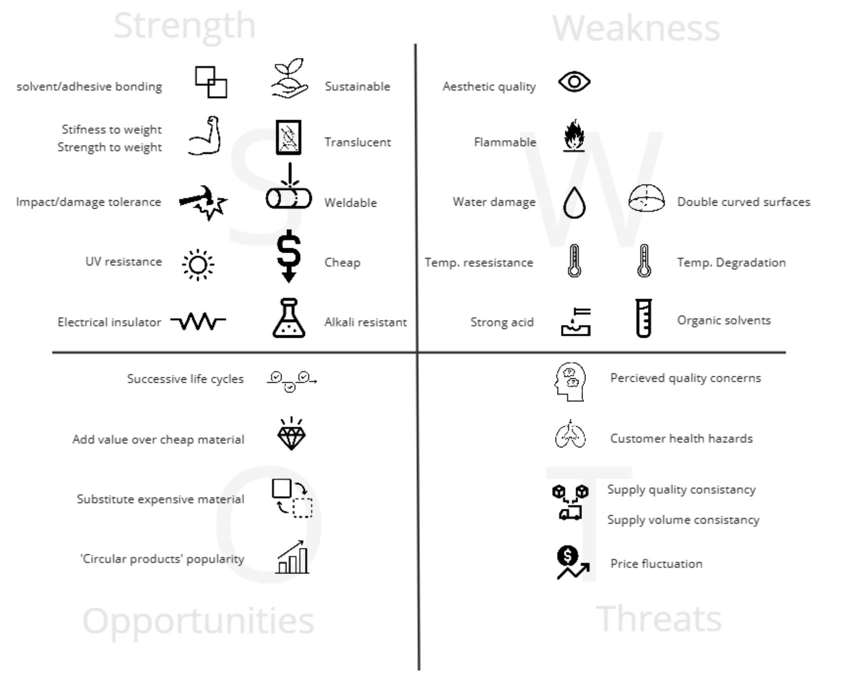

Figure 43 SWOT matrix of Glass/Elium laminates originating from a WTB

Table 13 Design requirements resulting from insights during the research phase of the project

ID	Description	type	Reason	Source	Means of compliance	Used for
1.1	The material used in the application can not get into direct contact with strong acids or organic solvents	Qualitative	Weakness of material	Chapter 4.3 - material properties of glass fibre reinforced Elium	Reasoning based on the design: Check if direct contact environment holds any of these substances	Final design
1.2	The material used in the application can not get exposed prolonged to water i.e. submerged or puddles forming, without a protective coating.	Qualitative	Weakness of material	Chapter 4.3 - material properties of glass fibre reinforced Elium	Reasoning based on design: Check if direct contact environment can cause long exposures to water i.e. damp sil. or concave shapes exposed to rain	Final design
3.1	The material cannot be used in critical structures of which failure could lead to serious injury or loss of life	Qualitative	Threat of (perceived) material quality and the quality consistency	Chaoter 4.3 - Opportunities and threats using blade waste	Reasoning based on application: asses if the application could lead to serious injury or loss of life	Idea selection
3.2	The material cannot be used in structures that have an elevated risk of ignition either due to vandalism or ignition sources being closeby without; a fire resitant coating or; other means of mitigating chances of ignition	Qualitative	Weakness of the material being flamable	Chapter 4.3 - material properties of glass fibre reinforced Elium	Reasoning based on design: check if application is prone to vandalism, then check if a coating is applied in the design	Final design

7. Design Vision

At the kickoff of the project I defined the mission of this project as being:

"Inspiring the industry to develop re-use applications of fibre reinforced thermoplastic wind turbine blades by making a demonstrator product made from re shaped (simulated) wind turbine material"

The design vision however focusses on the demonstrator which should communicate two elements in order to reach the mission goal: *Inspiring* and *meaningful*. This led to the following design vision:

'Show a broad audience the possibility of re-using TPC WTB material through reshaping with a meaningful and inspiring application'

7.1 Defining 'meaningful application'

In the context of the vision two aspects are identified which make an application meaningful: **Volume** and **exploiting material value**.

Currently initiatives such as Blade-Made undergo critique that their designs are mostly for show without using much blade waste. Although such critique can be disputed, a part of what makes a design meaningful is exposed: volume. I reason that by showing a demonstrator of an application of which it is immediately clear that large volumes of blade material are absorbed, adds to the meaning. As explained in 1.1 The problem of Wind Turbine Blade waste the value of the retrieved material should be kept as high as possible. Therefore the demonstrator should also try to retain value by making use of the technical value of the product. The technical value is formed by the material strengths identified in the SWOT of chapter 6. The most important material qualities that make the value are: high strength and stiffness and the ability to reshape the material.

7.2 Defining 'broad audience' and 'inspiring'

I define the audience to inspire as a mix of: **designers**, (composite) **engineers** and **government agencies** such as municipalities. Designers are part of the audience because this is the target group which will likely create the first wave of re-use applications. This will be most likely be a joint venture with engineers, in specific composite engineers since specific knowledge is required. Lastly, government agencies are included because national governments are a big user of high volume products and can set the example through their buying power.

Each sub group is inspired by different aspects of the demonstrator which is shown in Figure 44. A final definition of 'inspiring' was not formulated but the aspect listed in Figure 44 did help decision making in chapter 10. One aspect is clear: the audience should, without explanation, identify the demonstrator on its own without explanation as being the chosen reuse application.

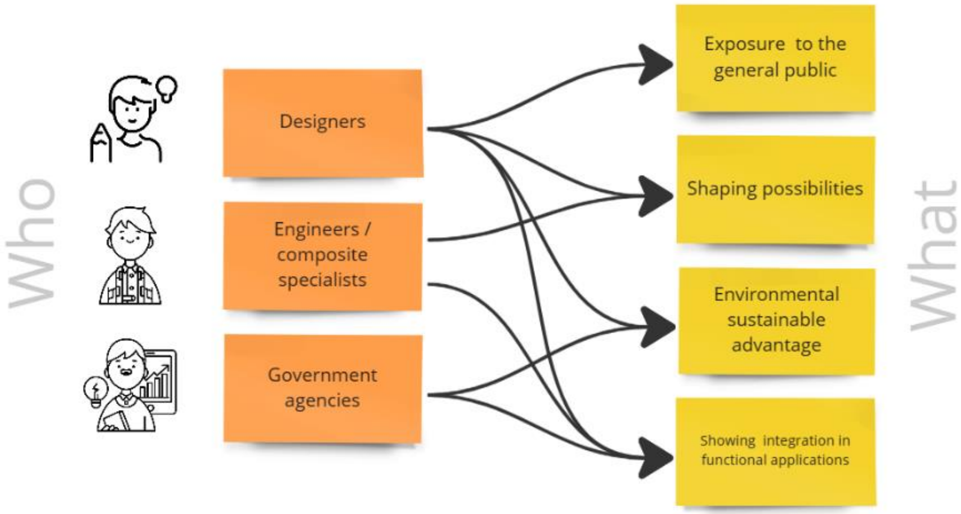

Figure 44 Demonstrator audience and what they might find inspiring

8. Requirements and selection criteria

In this chapter requirements and selection criteria used to find and select the right re-use application are presented. They differ from the ones set up for the final design and are therefore discussed separately. This also explain the numbering in Table 14.

8.1 Requirements

Complementing the requirement formulated in Chapter 6, the design vision sparked an additional requirement: The application should benefit from the technical value of the material. A third requirement was set up to ensure that making a demonstrator from the chosen application is feasible both in terms of machinery/tooling and time needed. The requirements can be found in Table 14.

8.2 Decision criteria

Next to a requirement the design vision also sparked some decision criteria. These criteria differentiate ideas based on how well they fit the formulated vision and are listed in Table 14 and are used in chapter 10. Criteria 3 can be seen as one aspect of criteria 4 but is used in a different stage of idea selection, hence the separate criteria.

Table 14 Requirements and selection criteria used to find and select re-use application ideas

#	Requirement description	Reasoning	Source	How to asses
2.1	The application should benefit from the technical value of the material i.e. strength and stiffness.	Exploiting material value is part of what makes a demonstrator meaningful. A meaningful demonstrator is part of the design vision.	Chapter 7 Design vision: Description 'meaningful application'	Reasoning based on application: asses if the application is at least semi-structural
3.1	The material cannot be used in critical structures of which failure could lead to serious injury or loss of life.	The threat of (perceived) material quality and quality consistency. Quality inspection efforts might mitigate the risk but are not developed yet.	Chapter 6 SWOT: Threat of supply quality consistency/certification	Reasoning based on application: asses if the application could lead to serious injury or loss of life
6.1	The application or a reasonable representation (e.g. a scale model or section) of the application should be able to be made using equipment available for this thesis and; in a reasonable time.	The goal of the project is to make a demonstrator.	Time management	Reasoning based on application
#	**Criteria description**	**Reasoning**	**Source**	**How to asses**
1	The application should maximize the amount of material being used.	The amount of WTB material volume that can be used with the particular application is part of what makes a meaningful demonstrator.	Chapter 7 design vision: Description 'meaningful application'	Subjective reasoning
2	The application should maximize the likelihood to inspire people to come up with and try out other applications.	The likelihood to inspire people with a particular application is a part of the design vision.	Chapter 7 design vision: Description 'Inspiring application'	Counting number of audience groups
3	The application should maximize the potential of showing the reshaping possibility of the material in relation to thermoset WTB's	The value of TPC WTB material over TSC is the re-shaping capability. When applications can also be made using TPS WTBs, TPC material value is not exploited.	Chapter 7 design vision: Description 'meaningful application'	Check the design already made with TPS WTBs. Asses how much reshaping is required for the application.
4	The application should exploit as much of the material strengths as possible.	The amount of value that can be used with the particular application is part of what makes a meaningful demonstrator.	Chapter 7 Design vision: Description 'meaningful application'	Count the number of material strengths benefitting the application
5	The application should make for a demonstrotor on its own (e.g. people should recognize the application)	The demonstrator fits the design vision less if people can not identify the product.	Chapter 7 Design vision: Description 'Inspiring application'	No physical context should be needed

9. Ideation

The design vision *'To show a broad audience the possibility of re-using TPC WTB material through reshaping with a meaningful and inspiring application'* mandates that in Ideation a meaningful application Idea is to be found. This chapter describes the activities and methods to find the ideas. An overview of all Ideas including a first round of elimination can be found in appendix I.

9.1 Brainstorming

To spark some initial ideas exploiting the strengths of the material, identified from the SWOT matrix, a brainstorm session with six design students and a PhD candidate from IDE's circular design lab was organized. In this brainstorm first some background was provided following with the material strengths and weaknesses. I asked the participants to first draw ideas individually after which the ideas were rotated. Groups were formed, ideas discussed and developed and finally presented at the end of the session. With the innovation manager from Heijmans a one on one private sparring session was arranged. Similar to the previous brainstorm, background and strengths/weaknesses were presented. After this the sparring partner started spewing ideas immediately. Both sessions led to some interesting ideas such as outdoor furniture and bridge elements.

Two ideas were investigated in more detail by company visits: the corrugated sheet and glass fibre piping. To systematically find Ideas, two methods found in the paper 'finding application for materials' were used (Landru, Bréchet, & Ashby, 2002) and are discussed in the following paragraphs.

9.2 Parasitical substitution

Landru, Bréchet and Ashby describe that this strategy is effective when the new material has properties that are similar to an established material and excels in one, replacing it on grounds of this differentiation. In this case the established material is chosen to be long glass fibres with an undefined but polymeric matrix (LGFRP). The property in which the new material (GF/Elium) will excel over the established LGFRP material was picked from the SWOT matrix. For this idea generation strategy, low material cost was chosen. In future effort other 'differentiators' such as the increased UV protection or environmental sustainable advantage can be picked. This strategy yielded interesting Ideas however a limited range and are questionable as some of them are quite critical in safety which does not fit the identified quality consistency threat of chapter 6. The generated Ideas can be found in Appendix J.

9.3 Optimized design requirements

In this strategy proposed by Landru, Bréchet and Ashby, the property profile of the material is matched with a library of applications. A concrete and comprehensive library of applications does not exist as far as I know because the range of applications is broad. Also the property profile of the material is not exactly known in terms of quantified properties. A design objective can however also function as an abstract description of the 'optimized design requirement'.

The general train of thought of exploiting the strengths of the materials by trying to match it with applications that benefit from this property yielded interesting results. I focused on three material aspects that stood out of the SWOT. The first one was the UV-protection which I transformed in the design objective of outdoor applications. The second was the ability to handle impact which was transformed in the objective of a lightweight structure that encounters impacts. The third was to make use of the material to act as a spring. The generated Ideas can be found in Appendix J.

10. Idea selection

This chapter described what steps were taken to converge from the ideas generated in the ideation to one idea.

Ideas like sheet piles, sailing boats and façade cladding were eliminated using requirements and a selection criteria listed in Table 15. These were for instance ideas already realized using thermoset blade waste, were too large to manufacture or safety critical.

Table 15 Requirements and selection criteria used to select one idea

#	Requirement description
2.1	The application should benefit from the technical value of the material i.e. strength and stiffness.
3.1	The material cannot be used in critical structures of which failure could lead to serious injury or loss of life
6.1	The application or a reasonable representation (e.g. a scale model or section) of the application should be able to be made using equipment available for this thesis and; in a reasonable time
#	**Criteria description**
1	The application should maximize the amount of material being used.
2	The application should maximize the likelihood to inspire people to come up with and try out other applications.
3	The application should maximize the potential of showing the reshaping possibility of the material in relation to thermoset WTBs
4	The application should exploit as many of the material qualities as possible.
5	The application should make for a demonstrator on its own (e.g. people should recognize the application)

The second round of elimination was performed using an adapted form of C-box (figure 41) which in its original form selects interesting Ideas by scoring each on two axis: innovativeness and feasibility. I changed these axis to represent the selection criteria 1: 'the application should maximize the amount of material being used' and 2: 'the application should maximize the likelihood to inspire people to come up with and try out other applications'.

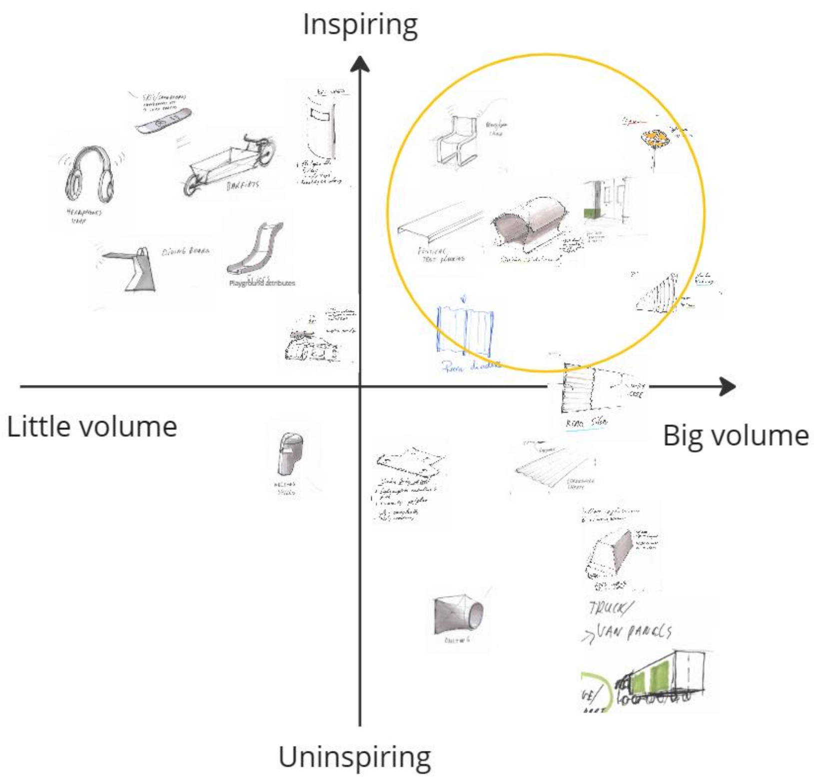

Figure 45 Adapted C-box for selecting the top right quadrant containing ideas that are scoring highest on inspiring and volume.

Now only three Ideas remained which can be seen in Figure 46. The train interior panel was eliminated because it would require more context to explain the audience what they are seeing than the lamppost and outdoor furniture and is thus scoring lower on Criteria 5. For the final selection decision criteria (3&4) were used which can be seen in Table 15. The lamppost outperformed outdoor furniture on criteria 3: ‘The application should maximize the potential of showing the reshaping possibility of the material in relation to thermoset WTB's’ because (outdoor) furniture has already been made from WTB material. The lamppost also makes the most use of the material qualities being the only one to exploit the electrical insulating property and which can be seen in Figure 46 Final selection between three ideas showing material qualities used in the idea.

Besides the higher scoring on decision criteria 3 and 4, the lamppost better showcases the ability of the material to be used in regulated, constraint applications. I therefore decided to continue with the lamppost.

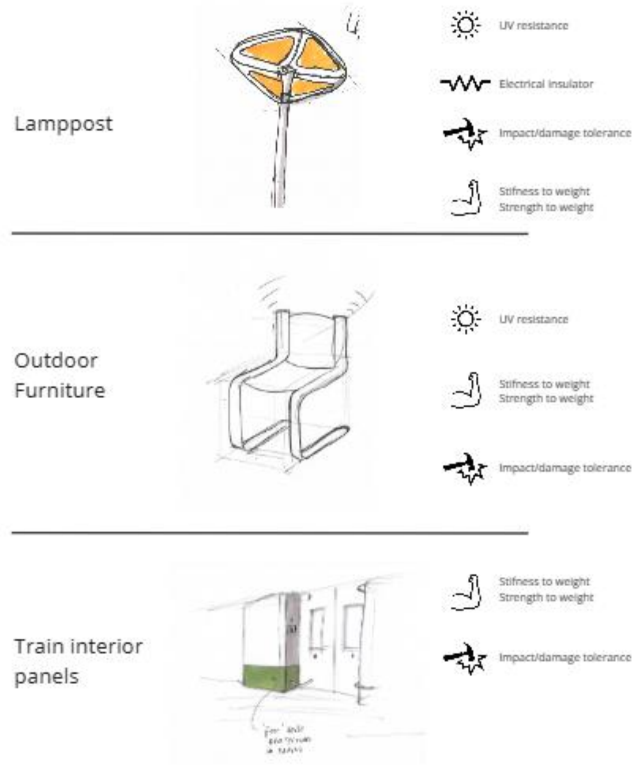

Figure 46 Final selection between three ideas showing material qualities used in the idea

11. Lamp post

In this chapter the benefits, opportunities and challenges of lamp post are described which created design opportunities and challenges for the final design which can be seen in Table 16 and Figure 47.

11.1 Benefits and Opportunities

The lamppost makes use of the strength and stiffness of the material. However, fibre orientation should be specified to make maximum use of this material strength which is an opportunity. Because the material is electrically insulating the lamppost does not have to be grounded according to E. Duits which saves on complexity (Duits, 2023). Although in lesser degree than the train interior panels, the lamp post also makes use of the impact resistance of the material. Designing with a UV-resistant material opens up the opportunity to leave out a coating. Playing with the translucency of the material also forms a design opportunity, previously left untouched. The post of the lamppost forms the opportunity to showcase single curved geometries with a relative small radius are possible. Even though shaping experiment 4 showed that strongly double curved surfaces (r=125mm) are difficult to form, the luminaire cover of the lamp post creates an opportunity to showcase the ability or disability of the material to be reshaped in a double curved geometry.

Table 16 Identified design opportunities and challenges

Opportunities	1	Optimize stiffness and strength by choosing the right fibre orientation
	2	(partially) Leave structure uncoated
	3	Play with translucency
	4	Showcase both single and double curved surfaces
challenges	1	Matching fixed panel dimensions to required lamp post dimensions
	2	Protect the post against vandalism with a focus on arson
	3	Integrate lamp post norms in design

11.2 Challenges

The first challenge identified is matching design requirements for the lamp post with the fixed thickness and size of the panels retrieved from the WTB. Secondly in contact with experts (Breederveld, 2023; Duits 2023; Alberts, 2023) it became clear that, especially for city lighting, vandalism is a problem. This makes for the design challenge of securing that the lamppost can resist vandalism and in particular arson. The mentioned experts also pointed out that lamp post have to comply to a set of norms. This forms the third design challenge.

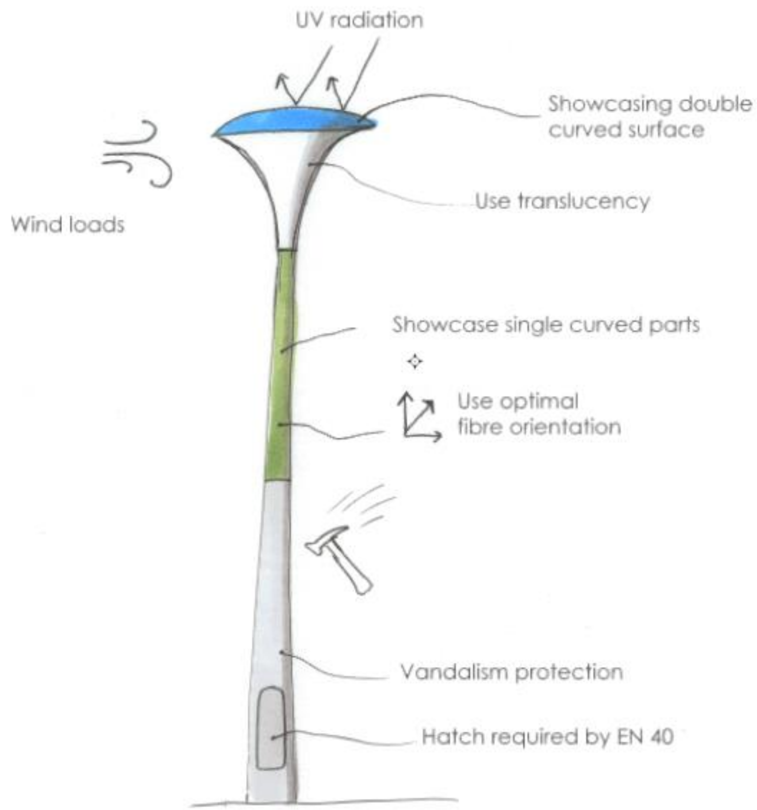

Figure 47 Benefits, Opportunities and challenges of designing a lamppost from TPC WTB material [Placeholder]

12. Application design

12.1 Final design scope and approach

The final design (   ) is a conceptual design of the selected re-use application of the lamp post. The design scope includes aspects like features and basic geometries but does not incorporate details like connection points. Components like the switch box and cabling are left out of scope. First, requirements were set up addressing design challenge 3 after which other design challenges were addressed as well as design opportunities. Finally the design aspect were combined in a CAD model.

12.2 Requirements

In contact with V. Alberts from the company Hydro, which produces aluminium lamp posts, a set of requirements for light masts was discussed: Norm EN-40 (Alberts, 2023). Design challenge 3 calls for integration of these requirements however a selection of the most important requirements was made. Strength, stiffness and geometric requirements are on a conceptual level and others like surface finish are on a detailed level which is deemed out of scope. requirements provides a complete overview of requirements.

Figure 48 Conceptual design of a lamppost made of TPC WTB material

Table 17 Final design requirements

Category	ID	Description	type	Reason	Source	Means of compliance	Implications
1. Material	1.1	The material used in the application can not get into direct contact with strong acids or organic solvents	Qualitative	Weakness of material	own	Reasoning based on the design: Check if direct contact environment holds any of these substances	Watch out for sour soil -> coating?
	1.2	The material used in the application can not get exposed prolonged to water i.e. submerged or puddles forming, without a protective coating.	Qualitative	Weakness of material	own	Reasoning based on design: Check if direct contact environment can cause long exposures to water i.e. damp sil. or concave shapes exposed to rain	Watch out for damp soil and concave armature shapes.
2. Performance	2.1	The mast should not fail under dead load of the armature and wind load specified as 35m/s	Quantitative	EN 40	EN 40, wind speed chosen around 12 Bft	Calculation with EN 40-3	Dictates wall thickness and/or diameter
	2.2	The mast should comply to maximum delfection specified in EN 40-3	Quantitative	En 40	EN 40	Calculation with EN 40-4	Dictates wall thickness and/or diameter
	2.3	The mast should be resistant to impact from brushcutters	Qualitative	Mowers can create impacts damaging the load bearing structure of the mast.	Hydro/EN-40	Reasoning based on design: check if a rotection ring is incorporated	Introduce a 'protection ring'
3. Safety	3.1	The material cannot be used in critical structures of which failure could lead to serious injury or loss of life	Qualitative	Threat of (percieved) material quality and the quality consistancy	own	Reasoning based on application: asses if the application could lead to serious injury or loss of life	Certain application Ideas can be eliminated
	3.2	The material cannot be used in structures that have an elevated risk of ignition either due to vandalism or ignition sources being closeby without; a fire resitant coating or; other means of mitigating chances of ignition	Qualitative	Weakness of the material being flamable	own	Reasoning based on design: check if application is prone to vandalism, then check if a coating is applied in the design	A fire resitant coating needs to be found
	3.3	The post should comply with impact protection category IK08 as specified in EN 50102	Quantitative	EN-40, protection of electric cables	EN-40	Five impacts arounf the post with a pendulum hammer or vertical free fall hammer	Wall thickness might be affected
4. Geoemtry	4.1	The post to armature interface should be 60, 76 or 90mm in diameter	Quantitative	This are the standard diameters for armatures on lamp posts	Heijmans/Hydro	Design check: check dimension	Tube diameter forming test 5
	4.2	The minimum radius for the base of the mast should be 114mm	Quantitative	minium radius for Hydro 4m urban poles to provide room for equipment	Heijmans/Hydro	Design check: check dimension	Conical shape of mast
	4.3	The Post above ground should be within 3 to 20m rounded in integers	Quantitative	EN-40	EN-40	Design check: check dimension	Design geometry
	4.4	The door height should be 400mm	Quantitative	EN-40 and Heijmans recommendation	Heijmans/EN-40	Design check: check dimension	Design geometry
	4.5	The minimum door width (projected) is 60mm	Quantitative	EN-40(minimum for door height of 400mm)	EN-40	Design check: check dimension	Design geometry
	4.6	The bottom of the door should be no less than 300mm from the ground level	Quantitative	EN-40	EN-40	Design check: check dimension	Design geometry
	4.7	Planting depth of the column is minimum 600mm. If calculation requires more length, either 800 or 1000mm can be selected.	Quantitative		EN-40	Design check: check dimension	Design geometry
5. Features	5.1	The post should incorporate a mast hatch including a reinforcement frame	Qualitative	Requirement for all lamp posts	Heijmans/Hydro	Reasoning based on design: check if a mast hatch is incorporated	Two or more layers of material reshaped at once or ins tages

12.3 The post

Incorporating the basic requirement and finding of the research, quickly a design was formed of the post. A circular cross section was chosen as this is the industry standard, by showcasing this it is assumed that the reshaping concept is taken more serious by industry experts.

Fibre orientation: design opportunity 1

As described in

4.3 Material properties, the strength and stiffness is largest in the direction of the fibers. As defined in 2.2.4 Layups and thicknesses, about half of the fibers of the retrieved TPC WTB material are in UD meaning the direction of the UD ply is the strongest and stiffest orientation of the panels. I therefore assumed that it would be best to orient the retrieved WTB panels such that the direction of UD fibers is along the length direction of the post as can be seen in Figure 49. The [±45°] bi-axial material conveniently takes up the torsional loads in the post.

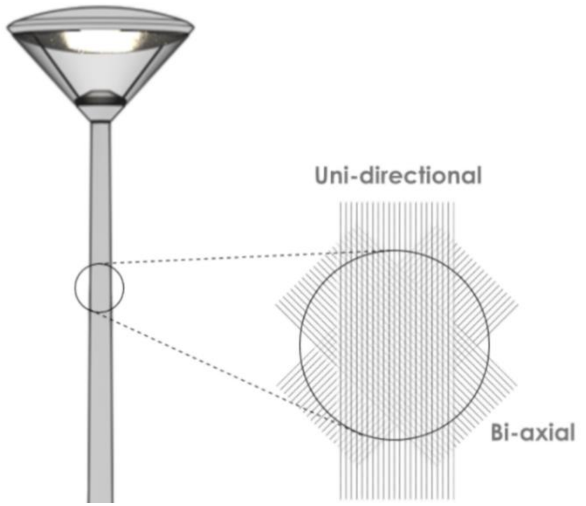

Figure 49 Optimal laminate orientation in the post

Basic shape: design opportunity 4 & challenge 1

The height of the post was set at 3m since this is the minimum required from EN-40. Masts of this size are almost all made from a single continues section. However as described in 3.2.2 Panel shape, size, fibre orientation and thickness, the maximum panel width along the UD fibers is 2m. This requires the post to be manufactured in two sections as can be seen in Figure 50. Larger posts would need more sections. Due to the thin wall thickness the step in diameter Is subtle and a filling area could potentially smooth out the transition.

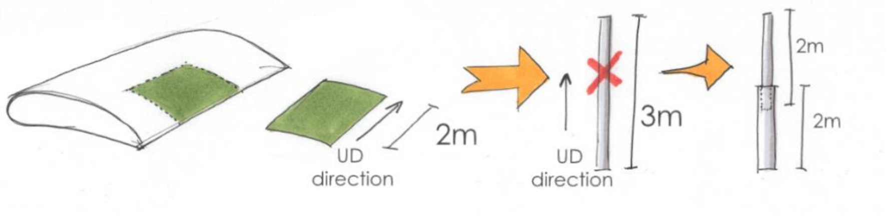

Figure 50 Maximum panel width restricts post height, a double tube geometry solves this

Even though EN-40 described other diameters are possible, both Heijmans and Hydro advised the minimum diameter of the pole at the base to be 114mm at the base and 60mm at the top. Since the posts showcases the single curved reshaping process I chose to make two conic sections which can be seen in Figure 51. The overlap area is chosen arbitrarily. From En-40 the minimum planting depth of 600mm was selected.

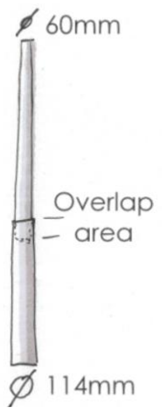

Figure 51 Max. and Min diameters found in the post

Post strength and deflection: Design challenge 1

In EN-40-3-3 , requirements on the strength and deflection of the post are provided. These requirements lead to a certain wall thickness or cross sectional area needed in order to comply. The panels retrieved from the blade have a given thickness however. It should therefore be checked if required wall thickness falls within the range of face ply thickness found in the reference blade. therefore three calculations were performed to check if strength and deflection of the post are compliant to EN-40:

1. Calculation of the post strength based on equations found in EN-40.
2. Calculation of maximum internal tensile strength using the Bernoulli-Euler beam theory to verify the strength calculation from EN-40.
3. Calculation of buckling strength of the post.
4. Calculation of maximum deflection using the Bernoulli-Euler beam theory.

The wall thickness was set at 2mm which is representative for thicknesses found in the reference blade. Values lower than 2mm resulted in strain values that were significantly out of bounds of what is expected in EN 40-3. The load applied to the pole was simplified as a point drag force acting on a sphere with a windspeed of 35m/s standing on top of the post (Figure 52).The post is assumed as a single element tube with constant diameter without a hatch. Three diameters are used as input: 60, 87 and 114mm. These are respectively the minimum, average and maximum diameter found in the final design. Granta's synthesizer tool was used to estimate GF/Elium laminate properties used in the calculation. A quasi isotropic layup [0°,±45°,90°] was assumed contrary to section 4.3. This resulted in a more narrow range of properties while the extra layer of 90° fibers should not strengthen or stiffen the laminate in the direction needed (0°). The results of the calculations can be found in table Table 18. The full calculation can be found in appendix K. Except when post diameter is unrealistically small (60mm) over the entire length, both strength and deflections are compliant to EN-40. This insinuates that it should be feasible to make a sufficiently strong and stiff lamppost of material retrieved from a TPC WTB. Strength and stiffness might not be the load cases dictating wall thickness or diameter however. Impact and crash protection are likely important as well. According to V. Alberts the level of crash protection is determined by the owner of the lamp post (Alberts, 2023). The post should at least comply to impact protection level IK08 specified in EN 50102. Since compliance is shown with tests, this was deemed out of scope. Therefore a more thorough analysis should be performed based on EN-40 which should have wall thickness and post diameter as variables.

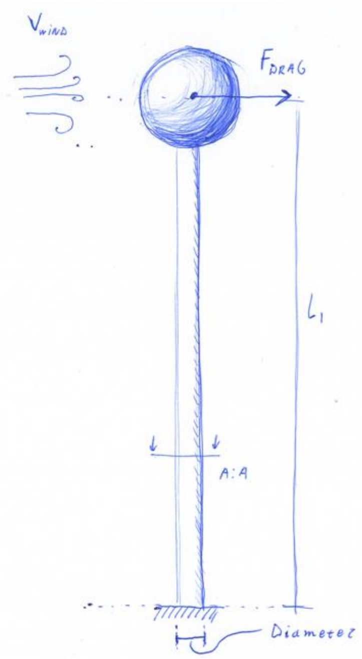

Figure 52 Load case of the lamppost. Wind acting on sphere which results in a drag force.

In case this analysis does result in wall thicknesses larger than what can be retrieved from the blade the following can be considered:

- Increasing the wall thickness by reshaping multiple layers of material at once, fusing them as the matrix is heated above the melt temperature (Figure 53).
- Increasing the wall thickness by shaping multiple post sections each with a stepdown in diameter and joining them.
- Increasing the stiffness by enlarging the diameter of the post, increasing the area moment of inertia.
- Adding stiffeners on the inside of the post.

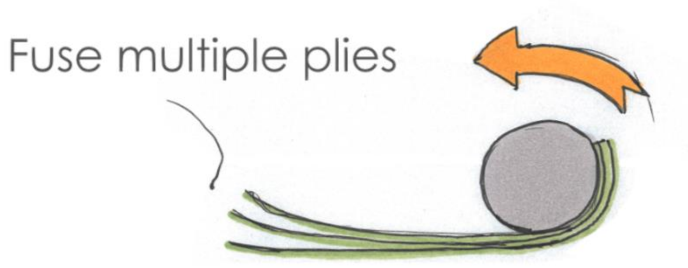

Figure 53 Multiple layers of WTB material can be compresses and rolled together fusing the layers.

Table 18

		Calculated values				Requirements (compliant if calc. value ≤ req. value)			
		From EN-40	From beam theory			From EN-40			Material limit
	Match numbers	1	2	3	4	1	3	4	2
Diameter	**Wall Thickness (mm)**	**Strength (ratio)**	**Tensile stress (Mpa)**	**Compressive stress (Mpa)**	**Deflection beam theory (m)**	**Strength ratio maximum**	**Buckling strength (Mpa)**	**Deflection limit class 1 (m)**	**Tensile strength (Mpa)**
60	1.1	0.23	18	18	0.28	1	815	0.12	979
87	1.1	0.15	8	8	0.09	1	556	0.12	979
114	1.1	0.15	5	5	0.04	1	422	0.12	979

Features: design challenge 1 & 2

According to EN-40 a mast hatch has to be incorporated to access the electronic components for installation and maintenance. Heijmans advised a hatch height of 400mm. The closed cylindrical profile of the post makes for a stiff structure which is compromised by the hatch opening. To compensate for this loss in stiffness, a reinforcement frame has to be installed. This reinforcement also helps to prevent damage from vandalism. This frame requires an extra set of formed sheets to be incorporated in the mast after initial reshaping (Figure 54). These can be welded or glued into place.

Most lamp posts have a polymer ring installed at the bottom of the pole to protect against impacts and shield the coating from salt and other chemicals. This ring is also incorporated in this design.

A small electronic box has to be incorporated in the mast. This requires the addition of attachment points which can also be made out of blade material and glued or welded into place. Grounding of the pole itself is not needed because the material is not electrically conductive, however the electronics and luminaire do need to be grounded.

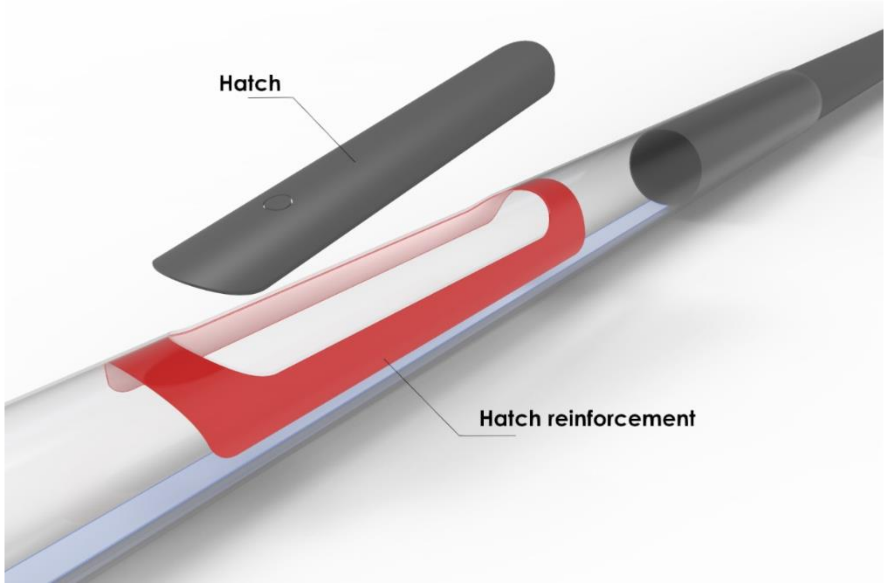

Figure 54 Hatch and hatch reinforcement

Coating: Design opportunity 2&3, challenge 2

To protect the lamppost from arson, either a fire retardant coating or protective sleeve is needed as shown in Figure 55. The advantage of a sleeve would be that it could also help protect the post against impacts and scratching. However the rest of the post should be coated for aesthetic reasons as well as protecting against low pH values resulting from sour soil at the bottom part of the post according to D. Breederveld (Breederveld, 2023). A coating can perform these tasks simultaneously and is therefore most likely. The coating could however complicate EOL as it could contaminate recycling waste streams and or be eco toxic.

Multiple fire retardant coatings exist which need further investigation. One example is Sika's Pyroplast line of coatings. The ST-100 variant is used in fire retardant composite aircraft engine bay components which need to comply to strict certification requirements ("Sika ® Pyroplast ® ST-100," 2022).

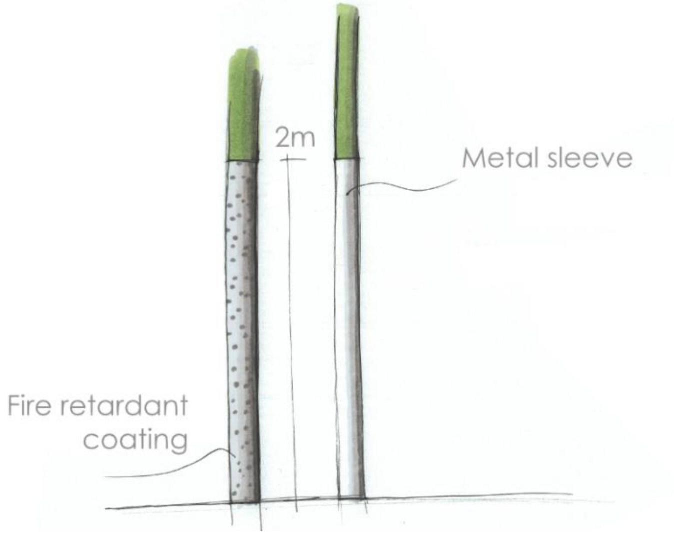

Figure 55 Two options to protect the material: coating or sleeve

Design opportunity 3 calls to play with the translucent nature of the material in the design. Due to the UV resistant nature of the material some parts could be left uncoated. This is only valid higher up the pole as here fire protection is less needed. In daylight a bichromate pattern can be seen while in darkness the transparent coated areas can be lit by placing a light in the post. Figure 57 shows the first trial of this principle. Here I tried to convey the reshaping method from a turbine blade to a tube shape in three icons. This aspect is more elaborated in 13.3 Finishing the demonstrator since showing the reshaping process is envisioned for the demonstrator only.

For the final design a gradient at the top of the post was envisioned which becomes brighter nearer to the luminaire to make a 'soft' transition of brightness. I chose to refer to the origin of the mast material by making a pattern of wind turbine blades. A rendering of the end result can be seen in Figure 56. The envisioned effect is not yet fully reached but this can be iterated on in future efforts.

Figure 56 Pattern of uncoated area

Production process

The envisioned process of producing TPC lampposts is an adapted form of roll forming (Figure 58). This process, normally used to make cylinders from sheet metal, forms a blank into a cylindrical shape by a set of rollers ("Roll forming - how to make a metal tube," n.d.). A critical adaptation to form TPC's is to heat the blank and/or the rollers. The forming happens gradually which might be beneficial in preventing material defects. Finally, to gain strength and stiffness from the circular cross section it needs to be closed. In the industrial roll forming process this is achieved by feeding it through a welding station directly after forming. The GF/Elium material is weldable as discussed in

4.3 Material properties which makes the basic concept of this technique feasible. Conical shapes might be hard to manufacture with this process however by moving the rollers while feeding the material could facilitate gradual diameter changes needed for a conical geometry.

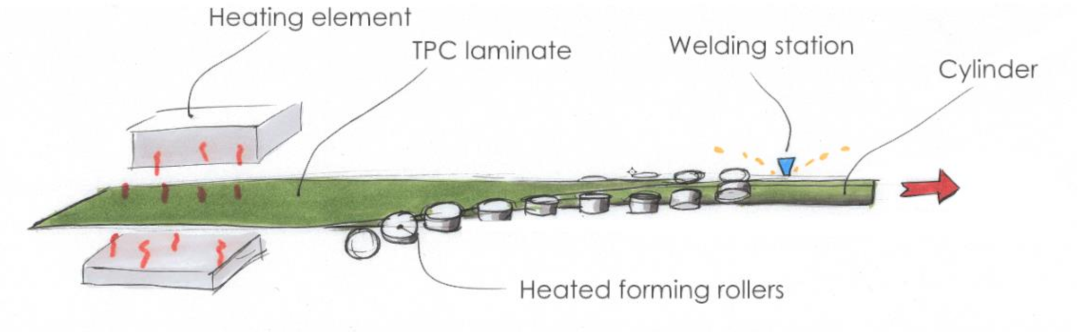

Figure 58 Adapted roll forming as envisioned production method for TPC lampposts.

Figure 57 Trial of leaving the material partially uncoated with a backlight

12.4 The luminaire

Heijmans provided an luminaire for use in the demonstrator model (Figure 59). It is a standard model used by Heijmans and weighs 9.6kg.

Luminaire Cover: Design opportunity 4

The design of the luminaire itself was deemed out of scope, however the cover provides an opportunity to show double curved surfaces. EN-40 provides little requirements on the cover so the design is based on the provided luminaire. Shaping experiment 4 showed that the material and production process used do not provide satisfactory results for strongly double curved surfaces. Therefore a shallow cover was designed with a small depth to diameter ratio. Because of geometric conditions a 'spacer' had to be incorporated to account for the reduced depth which is shown in Figure 59.

The cover can also showcase the UV resisting quality of the material by omitting a UV blocker in the coating or not coat the cover at all.

Figure 59 exploded view of the luminaire, spacer ring and luminaire cover

Production process

A derivative of matched die forming is a logical process for producing the luminaire cover. Here the laminate is heated after which it is pressed between a heated male and female mould. This process is rather quick and tolerances can be as close as the design requires(Michael C.Y. Niu, 2000). The envisioned shape of the spacer ring is harder to manufacture with the WTB material as shaping experiment 4 showed. The luminaire cover can however be extended, making the spacer ring a single curved geometry which is shown in Figure 60. This geometry should be thermoformable on a conical mould.

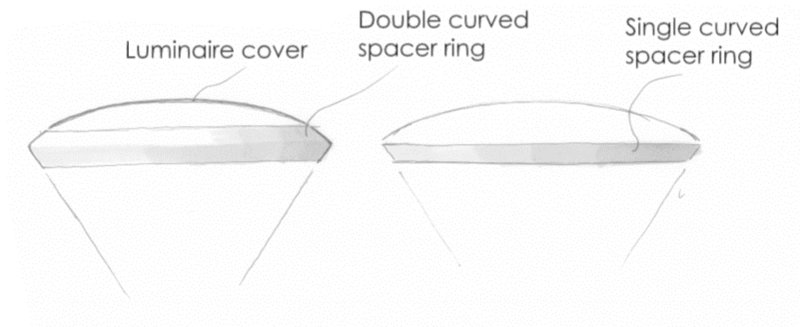

Figure 60 Current (left) and adapted spacer ring (right)by enlarging luminaire top, simplifying the ring's geometry

13. Demonstrator

13.1 Demonstrator embodiment

A demonstrator is made to evaluate earlier findings on reshaping. This demonstrator is based on the final design presented in chapter 12, but differs in some aspect which can be seen in Table 19.

Table 19 Adaptations from application to demonstrator design and reasoning.

Adaptations	Reason
Three instead of two sections	Limited mould size restricts section height.
Cylindrical instead of conical sections	Conical moulds would be needed which complicates manufacturing without yielding additional insights.
Glue strips instead of welding to close sections	Welding does not yield additional insights while increasing complexity
Use of original armature cover	Demonstrator audience does not see the cover on top of a 3m post
Aluminium instead of TPC hatch reinforcement	TPC reinforcement would require more time without yielding additional insights
Three section detachable instead of fixed	Simplifying logistics
Laminate rolling as in 'shaping experiment 5' instead of roll forming	Reducing complexity; Feasibility within project scope

The change from conical to cylindrical post sections resulted in a base diameter of only 75mm compared to the 114mm required from EN 40. This step down in diameter lowers the strength of the demonstrator. An internal stress calculation was performed to check if the post with a 9.6kg luminaire at the end could stand under an angle of 45° without failure. This was positively confirmed.

The luminaire cover was placed besides the lamppost to show the double curved surface up close (Figure 61).

Figure 61 Unfinished demonstrator with the separate luminaire cover

13.2 Demonstrator manufacturing

Manufacturing of the demonstrator started with the reshaping of post sections and the luminaire cover. This section shows the manufacturing methods and results. The results are discussed in chapter 14.2 Evaluating the demonstrator

13.2.1 Shaping post and luminaire cover

Method

The same basic method of laminate rolling was used as shaping experiment 5 (appendix E), however this was expanded as the length of laminates increased. The rolling setup can be seen in Figure 62 which also shows the setup seen through an IR camera which was used to check temperature homogeneity.

Also the luminaire cover was shaped following the same method used in earlier experiments by heating up the mould, laminate and vacuum bag in an oven and applying vacuum pressure once temperature reached 140°C.

Table 20 shows for both post and cover the known process parameters.

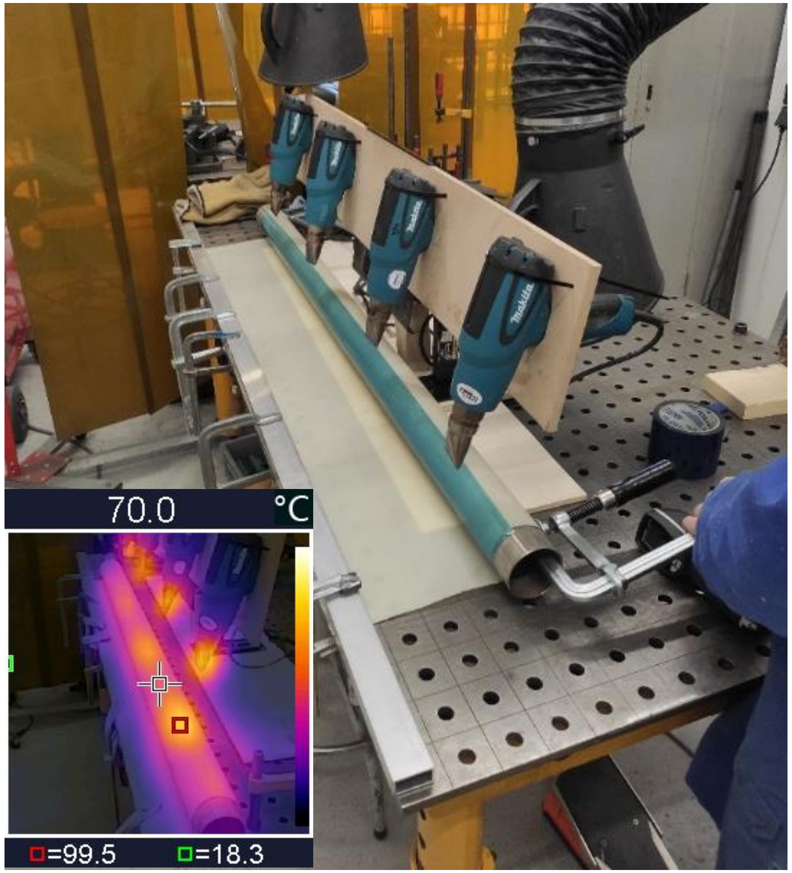

Figure 62 setup of laminate rolling (normal and IR camera)

Table 20 Information about the goal, laminate and process parameters for the manufacturing of the post and luminaire cover

			Laminate		Process paramaters							
#	Title	Goal	**Layup**	**thickness (mm)**	**Method**	**Applying heat**	**Reshaping temp (°C)**	**Reshaping pressure (mBar)**	**Time above Tg (minutes)**	**Mould shape**	**Radii (mm) max, min**	
1	Three post sections	Scaling up laminate rolling from 300 to 1300mm	812g/m^2 bi-axial [+-45°] + 600g/m^2 UD of length axis mould	1.1	Laminate rolling'	Convexion/ conduction	120-140	Unknown	Unknown	Cylindrical	35	30
2	Armature cover	Assessing material reshaping performance for double curved surface	812g/m^2 bi-axial [+-45°] + 600g/m^2 UD	1.1	Vacuum bag forming	Convexion	140	15	18	Double curved	1000	

13.2.2 Results

Three types of defects in the post sections were visually identified:

- White speckles (Figure 65).
- Burn marks (Figure 67). This is due to placing the heat gun too close to the laminate.
- Fibre breakage or matrix cracking forming a white line along the length of the tube (Figure 65). This defect appeared when reshaping at temperature below 120°C.
- Laminate twist in the post sections (Figure 66)

Figure 66 shows all components to make the post including the aluminium reinforcement section ready to be assembled. After assembly some air pockets were discovered in the glue which closes the post section. These were filled up using a syringe after curing (Figure 65).

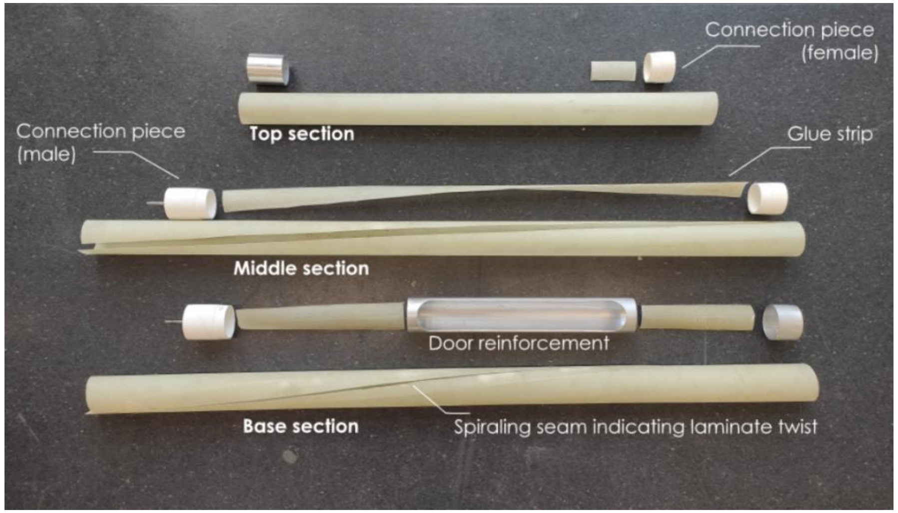

Figure 66 The components of bottom, middle and top post sections ready to be assembled

The luminaire cover showed three types of material defects:

- fibre buckling which results in large wrinkles which can be seen in Figure 64.
- Matrix Browning (Figure 63)
- Laminate twist

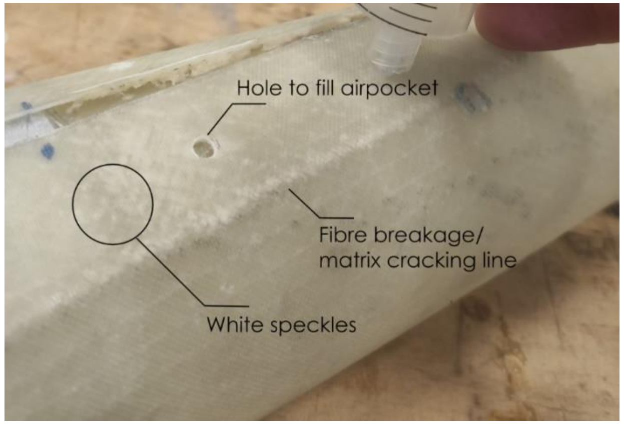

Figure 65 closeup of a post section showing defects

Figure 67 Burnt matrix

Figure 64 Closeup of the luminaire cover showing fibre buckling

Figure 63 luminaire cover (right) and virgin laminate (left)

13.2.3 Discussion

The location and direction of the white lines formed by suspected fibre breakage or matrix cracking corresponds directly to the gaps between the bands of UD tape in the layup. These gaps create locally weaker lines in the laminate. The combination of insufficient temperature and the weak spots in the laminate resulted in this defect. These weak spots do not exist in the 'real world' layups however, which suggests that this material defect will not occur when reshaping actual TPC WTB laminates. As discussed in 4.2 Re-shaping experiments the material defects of the white speckles is not caused by the reshaping. The burn marks are the result of a mistake.

The reason for the fibre buckling found in shaping the luminaire cover is believed to be partially due the prevention of intra-ply shear caused by stitching patterns. Other fabrics allow the fibers to change relative orientation and thus intra-ply shear (Mohan, 2015) (Figure 68). The hindrance of this deformation mechanism and the performance of this material to form double curved surfaces is therefore directly linked to the structure of the material.

The other contributor to this wrinkling is the process used. The vacuum bag method poorly prevents fibers from moving out of plane. Diaphragm forming does restrict out of plane movement and could thus produce double curved surfaces without wrinkles (Michael C.Y. Niu, 2000). In diaphragm forming the laminate is tensioned between two diaphragms where a pressure difference presses the diaphragms including laminate over the desired mould shape (Figure 69 basics of diaphragm forming. P+ is positive pressure, p- is negative pressure).

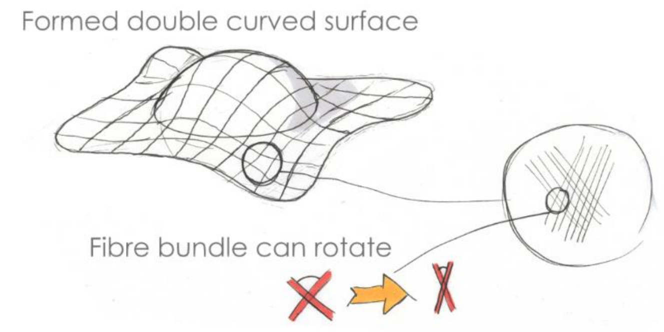

Figure 68 In a woven fabric without stitching (e.g. twill), fibre bundles can rotate allowing forming of double curved surfaces

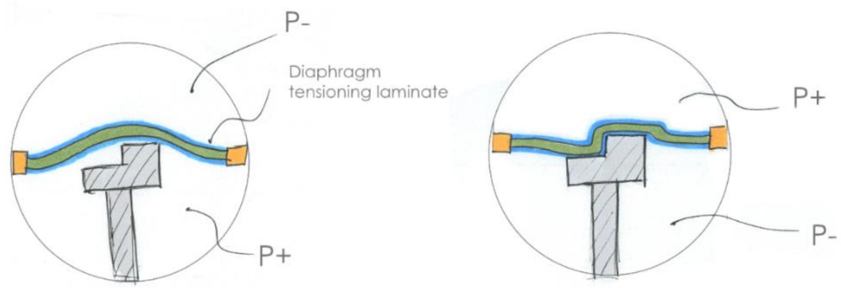

Figure 69 basics of diaphragm forming. P+ is positive pressure, p- is negative pressure

The panel twisting found in both the cover and post sections is a result of the asymmetric and unbalanced nature of the laminate (Davis, 2014).

The browning of the luminaire cover occurred while the shaping temperature (140°C) was significantly lower than the first degradation step of PMMA which is 180°C (Nikolaidis & Achilias, 2018). This suggests that the browning might not signal degradation which was assumed earlier.

13.3 Finishing the demonstrator

Following the illuminated pattern and story design proposed in 12.3 The post the post sections were masked and coated. The result of the pattern design can be seen in figure 70. The illuminated reshaping story showing a WT, WTB, extraction of a panel, laminate rolling, resulting tube and finally the lamppost can be seen in figure 72. Some rectangles were also left uncoated to show the audience the material itself which can be seen I figure 71.

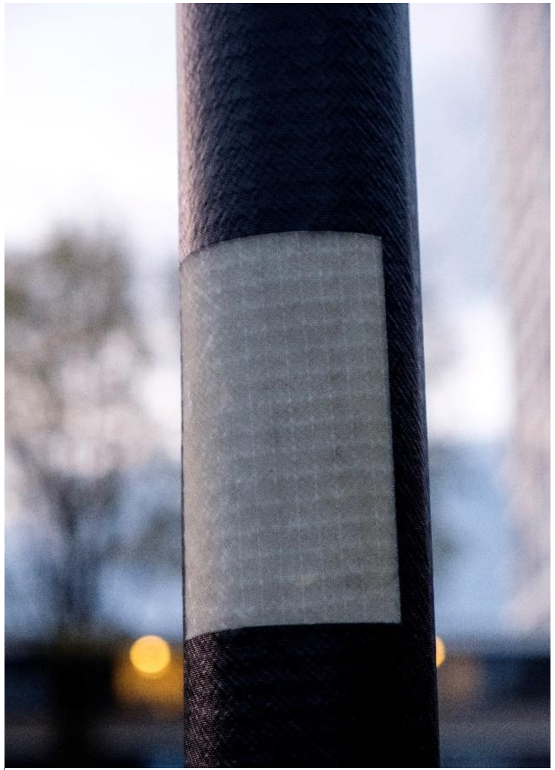

Figure 71 Closeup of the post, showing the material

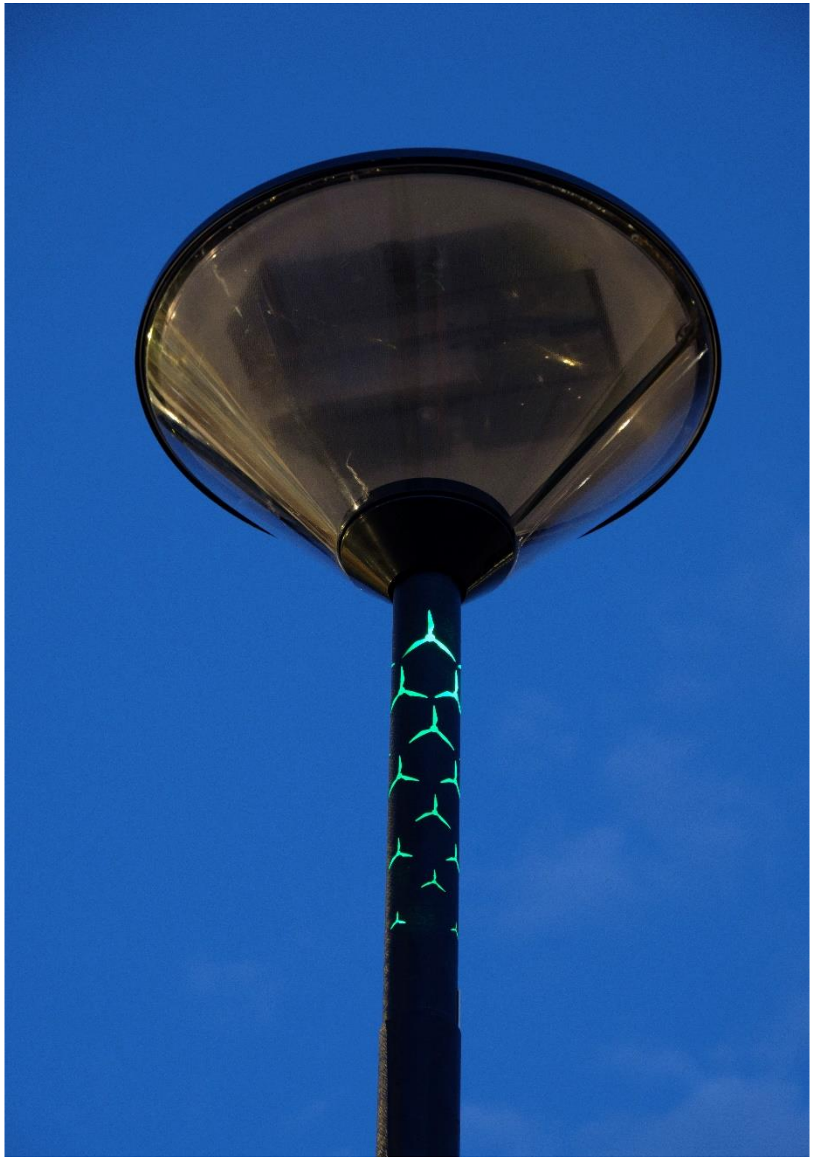

Figure 70 The lighted pattern works as intended

Figure 72

14. Evaluation

14.1 Evaluating the design process

Using the RTDP method

Using the reflective transformative design method proved to be a successful way of structuring an explorative research and design project. The ability to switch between design and research activities often and reflecting on the gained knowledge or output proved valuable. Tinkering with material is a good example of this. A ‘doing activity’ of shaping a piece of material around a half cylinder, reflecting on the finding, the potential to make tubular shapes, then feeds into a ideating activity of generating application ideas. Later on, a validation step confirmed that making tubular shapes is feasible. This method facilitates iteration to a bigger extent than a more classical approach like the double diamond.

Understanding the material

A large part of this project was dedicated to understanding the material at hand which I think was crucial. Without quickly gaining a feeling of the shaping limitations, strengths and weakness of the material and process parameters, envisioning meaningful applications would prove difficult. This tinkering approach of understanding the material is a fast way to explore possibilities and limitations but is less suited for accurate and repeatable material research purposes.

Ideation methods

At first I started generating ideas based on tinkering with the material as described above. However, to broaden the application ideas, a more pragmatic approach was taken by using two methods proposed by Landru, Bréchet and Ashby: Substitution and optimized design requirements, as well as brainstorming with peers and experts. In the brainstorm sessions it was key to let the participants understand the material as the TPC material is not commonly known. At this time I did not fully grasp the material and thus effective transfer of this knowledge proved difficult. Additionally, the ‘substitution’ and ‘optimized design requirements would have benefitted from a better understanding of the limits of the material as many ideas were generated that use strongly curved double surfaces. This later proved to be a weakness of the material. However, the methods themselves performed well, especially the optimized design requirement method. Transforming the strengths of the material into design objectives efficiently yielded ideas making use of material value. The substitution method did not yield many or valuable ideas. Part of the reason could be that trying to substitute a well-integrated and optimized material with a highly specific and partially understood material is difficult. A wider scope of materials to substitute might yield more valuable ideas.

Formulating a design vision also proved valuable as this provided direction in the design process as well as yielding selection criteria and a design requirement. This structured the idea selection. While evaluating the demonstrator, the design vision was used as well.

panel classification

After segmentation, the panels were classified based on characteristics. This classification was used to retrieve information for producing laminates but it proved most valuable in designing the lamppost. During the lamppost embodiment, panel information could be quickly retrieved which made it a valuable addition to the design process.

14.2 Evaluating the demonstrator

Evaluating fit to design vision

In Chapter 7, a design vision for the application and demonstrator was drafted as:

'Show a broad audience the possibility of re-using TPC WTB material through reshaping with a meaningful and inspiring application'

Evaluating the fit of the demonstrator to this vision shows if the design goal is reached and if not, what should be changed in future efforts. First the meaningful part is evaluated followed by the inspiring part.

'Meaningful'

In Chapter 7 the meaningful part of the vision comprised of two main elements: volume and use of material value. Based on a 'back of the envelope' calculation which can be found in Appendix L, it can be assumed that the complete annual demand of lamppost can be saturated by TPC WTB material. This assumes that also taller lampposts are made with this material (>3m). However in this calculation it assumed that only about a third of the total blade mass is useable for this application which leaves a major part of the yearly supply of WTB material, unused in this application. Other applications might however use this material. These figures need a more detailed calculation. However a conclusion can be drawn that the chosen application does indeed absorb a large quantity of blade waste single handedly absorbing about a third of the annual WTB material supply. The demonstrator therefore does fit the design vision for 'volume'.

Use of material value was used as a selection criteria and thus the demonstrator does also fit to this part of the vision using the material strength, stiffness and UV resistance. Use of the impact resistant quality of the material is not evaluated.

'Inspiring'

As presented in Chapter 7 designers, (composite) engineers and government agencies should be inspired based on four aspects: exposure of the application to the general public, showcasing shaping possibilities, making clear that the application has an environmental sustainable advantage and finally, showing that the application is functional (Figure 73).

To assess the fit of the demonstrator to these four elements, 10 short interviews were conducted with:

- Five design students
- One experienced designer
- Three engineering students (two with composite design experience)
- One person from TU Delft campus real estate managing public lighting (real estate management could be considered a representation of a government organization)

First the respondents were introduced to the topic and the material. After making sure this was clear, the respondents were asked to generate re-use applications themselves. After the respondents ran out of ideas they were asked if the demonstrator helped them guide their thought process in finding ideas. The interview questions can be found in appendix M.

Eight respondents confirmed that they were inspired by the post showing shaping possibilities. However five admitted that they were limited thinking in tubular shapes because the demonstrator heavily focusses on this type of shape. Two respondents were not inspired by the reshaping possibilities. One of them responded that he was zooming in on the material, getting inspired by its surface finish and the other did not consciously make the link that the tubular shapes were actually formed from plate material. Two respondents mentioned they were inspired by the public nature of the lamppost and generated ideas for the public space. The public lighting manager generated ideas mostly based on circular product integration.

The acknowledgement of respondent that they were inspired by the public nature of the demonstrator confirmed people are inspired by exposure to the general public. Interestingly, this was also linked to the environmental sustainable advantage as the respondents mentioned that this quality of the material should be communicated in other public space designs as well. It is assumed that this was also the main driver of inspiration for the public lighting manager since this person generated mostly circular product ideas. Inspiration through showing integration of the material in functional applications was not consciously confirmed by any of the respondents. It is however likely as most application ideas generated were functional.

From these interviews it can be concluded that the demonstrator does fit the inspiring part of the vision. However, the audience might be inspired in a narrow band of application shapes, that of tubular structures even though the luminaire cover was also showcased. In future demonstrators, more of the reshaping possibilities must be shown without a clear focus on one to avoid this application 'tunnel vision'.

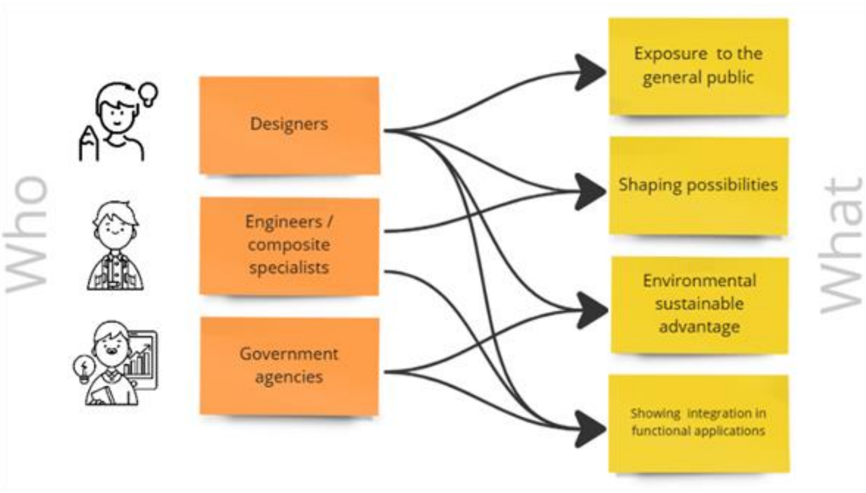

Figure 73 Demonstrator target group (who) and what they are inspired by (what)

Material reshaping performance

As discussed in 13.2.3 the performance of the TPC WTB material to form double curved surfaces is directly linked to the structure of the material. Even shallow double curved surfaces like the one formed on the demonstrator luminaire cover (r=1000mm) result in major material defects. It can be concluded that the TPC WTB material performs well for single curvature reshaping efforts but not in double curved deformations made by vacuum bag forming. This means that applications which only use single curved surfaces should be feasible but that double curved features might need local incisions to allow the material to deform (Figure 74) or that a certain level of wrinkling should be accepted.

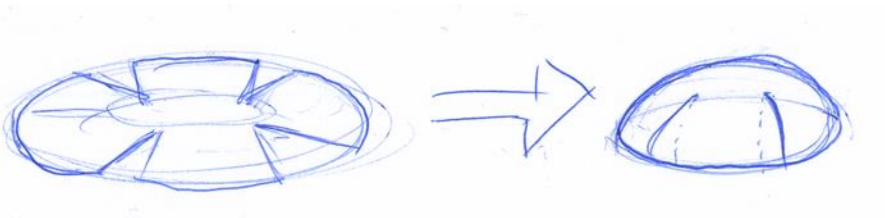

Figure 74 Forming double curved surfaces might require local incisions in the material to prevent wrinkling [Placeholder]

The material however does perform well in shaping single curvature geometries as seen in the demonstrator which has a minimum single curved radius of 30mm.

Sustainability

Reshaping energy usage

In literature, structural re-use circular strategy is described as preserving material quality and value with a relatively small investment of energy and resources (Joustra, Flipsen, & Balkenende, 2021). To make reshaping more environmentally sustainable than manufacturing virgin products the total sum of resources and energy used should be lower. It is likely that in reshaping, less resources are used as the material does not have to be extracted from the earth. However the energy demand should be carefully monitored to not outweigh the gains in resource reduction.

Core material waste

In the demonstrator and the actual design of the lamppost, monolithic panels are used. It is assumed that after the face plies have been split from the core material, the core material can be considered waste which could be recycled. Even though the density of the core material is low, the bulk of the volume of the sandwich panels is core. With a rough calculation (Appendix L) it is determined that about 1650 kg (15 wt%) material is wasted for the usable panels within the spanwise scope (mid-span). This is a significant amount.

Beyond the first loop

The lifetime of the material can be prolonged significantly when used in the lamp posts. However this application will eventually also face EOL where again circular strategies should be applied. By using structural re-use through reshaping, material is liberated and reshaped into new applications. However it is unsure if the material can be re-shaped again without major loss of mechanical properties. For instance, the matrix material could degrade per heating cycle as it is not developed for multiple heating cycles. Additionally, the limited size and elongated shape of retrieved panels might prevent another cycle of structural re-use. When structural re-use is not desirable, feasible or viable, recycling could become the strategy to pursue. Developments in retrieving both matrix and fibers from the laminates by solving the matrix is promising and could mean that material value is still preserved (Boisgontier, 2022). Special care should be given to the coating system applied on the post. This coating has to be removed to prevent contamination of recyclate after recycling. The coating might be left untouched if the coating can be reshaped as well.

15. Limitations & recommendations

15.1 Recommendations for future research

The performance of sandwich panels in reshaping was not researched in this thesis. An assumption was made that the face plies can be removed from the core. This assumption needs to be validated before any claims can be made on feasibility and viability.

The extent, location and effect of aging effects for a TPC WTB are not well understood but could affect properties of the retrieved panels. Also the reshaping extent and methods could alter properties which was not researched in this study. Mechanical tests performed on coupons from virgin, retrieved, heated and reshaped panels comparing mechanical properties should cover these limitations. A loss in mechanical properties should also provide insights if a second reshaping cycle is possible.

The method of material defect identification should also change from visual inspection to more professional and accurate methods starting with optical microscope imaging of cross sections.

Even though some boundaries in reshaping extent were identified in this thesis (double curved) more research is needed. The minimum single curved radius tested was 30mm but it is suspected that smaller radii are possible. This thesis is inconclusive about the contribution of the process in the material defects arising on a shallow (r=1000mm) double curved surface.

The layup of the test panels should be more representative. In this study the UD fabric was of lower weight and width than in real WTBs as discussed in 4.1 Simulated WTB laminates This could have resulted in falsely positive results.

The lack of parameter control in the reshaping processes used int his project complicates the repeatability of the experiments as well as distinguishing cause-effect relationships in analyzing material defects. It is recommended that more professional methods and equipment is used in future experimentation.

More research is also needed in determining the design of TPC WTBs since this determines segmentation and thus panel characteristics. This thesis used information from a highly theoretical design which might be unrepresentative of future implemented designs.

15.2 Recommendations for designers

In the embodiment phase a more complete library of panel characteristics would provide the designer with a better tool for matching application requirements with panel characteristics. This library should not only provide maxima and minima for size and curvature but also material thicknesses for every class covering the full blade span. Currently this information is only known for the 30-45m section of the reference blade.

When designing applications which will substitute current products, LCA's should be made and compared with the current form of the application as using a waste material does not automatically mean lower environmental impact. In the total sum of energy and resources, it could occur that the current application has less environmental impact than the replacement when the energy demand for reshaping is big.

As discussed in Material reshaping performance laminates experience twist. To counter this twist, a stabilizing ply could be laminated on the panel in the direction of UD fibers [0°]. This makes the laminate balanced.

Reshaping of panels liberated from the skin of the blade was the focus of this thesis. About a third of the weight of the blade mid-section is in the spar caps however. Finding applications for this structure is key when striving to re-use as much material as possible. Applications like flooring panels, concrete rebar or mixed material application such as a bus shelter come to mind. Also the root (40 wt%) and tip (2 wt%) sections should be used.

I want to highlight one particular idea found earlier in the project which should gain more attention: corrugated sheet. This is an application which uses large amounts of material, proved easy to reshape and could possibly be flattened again.

15.3 Recommendations for blade manufacturers

The insights gained in this thesis also result in some recommendations for TPC WTB manufacturers. If during the design of the blade, structural re-use is taken into account, it is recommended to alter the type of fabrics used. The current non-crimp fabrics prove difficult to reshape in double curved surfaces. This could limit the diversity of re-use applications. Instead woven fabrics such as twill provide excellent drapability at the cost of some stiffness and tailoring options. Secondly, sharing of information on material composition and structure of certain areas in the blades would enable designers to more efficiently and accurately design applications.

16. Conclusion

At the start of the project I formulated the following missions statement of the project:

"Inspiring the industry to develop re-use applications of fibre reinforced thermoplastic wind turbine blades by making a demonstrator product made from reshaped (simulated) wind turbine material."

Before a demonstrator product could be designed, some initial research had to be performed on TPC WTB material which started by identifying a knowledge gap. This gap was defined as: a lack of knowledge exists about the characteristics of material retrieved from a TPC WTB and how this material is affected by reshaping it to make it suitable for new applications. This knowledge gap was transformed into the main research question:

To what extent can TPC WTB material be segmented and reshaped and how does reshaping affect its characteristics?

To answer this question, first the design of a TPC WTB was explored with literature research and expert opinions. Segmentation patterns, literature, expert opinion and material tinkering were used to define the characteristics of the retrieved material. Reshaping experiments both on isolated shapes and material made for the demonstrator provided insights in the forming limits of the material and what process parameters are important. These activities led to the following main insights:

- The reference TPC WTB can be segmented using a pattern based on structural elements in the blade such as ribs or spar caps. At the intersection between these structures, material composition changes drastically making it a logical segmentation boundary.

- The TPC WTB material can be reshaped in single curved surfaces with relative ease. Tests showed that the minimum radius was 30mm. Due to the material structure, double curved surfaces are challenging and could prove to be not possible at all. From tests, the maximum double curved radius was 1000mm but still resulted in wrinkling.

- Reshaping affects the characteristics of the material in that it changes colour which possibly indicates matrix degradation. Other defects resulting from reshaping are: fibre waviness, buckling, breakage and matrix cracking. These defects likely affect the mechanical properties of the reshaped part. The extent of reshaping also changes the panel characteristics indirectly as curvature radii under roughly 500mm in the reshaped part need monolithic panels which asks for face ply separation.

Evaluations showed that the demonstrator indeed inspires people. New application ideas were generated and participants consciously make the link between reshaping showcased in the demonstrator and their thought process being influenced by it.

To conclude: the material performs well in forming single curved surfaces and can be used in a functional product. Combined with the finding that a significant amount of blade waste can be re-used in only one application, lampposts, makes structural re-use through reshaping an interesting EOL strategy which should gain more attention from researchers, designers and policy makers.

Personal reflection

In this reflection I start by reflecting on the personal (learning) ambitions which were drafted in the project brief.

I wanted to gain experience working with natural fibre reinforced composites. This did not work out as expected since I could not acquire heavy-weight non-crimp natural fibre fabrics. Unfortunately, I put in considerable effort and time in finding, contacting and meeting companies that made natural fibre reinforcements such as Groupe Depestele, Bcomp and BPREG. I realize that the decision to work with fiberglass reinforced plastics was made too late. This brings us to the next topic: that of uncertainty.

The second personal learning ambition was to find out how I would handle a practical project which had a great deal of uncertainty. The amount of uncertainties certainly complicated decision making. I learned that within an explorative study, there is no optimal decision. Each unexplored path will generate useful results when chosen. However, one path can feel more relevant than others. In the future I should be more pragmatic and direct. For instance, in deciding whether to move forward with sandwich or monolithic panels I was afraid to assume that face plies could be split from the core. I should have realized that within the limit time scope available I couldn't afford to pursue both directions even though I felt unsatisfied. In line with this is that I should have focused on activities that contribute directly to the outcome of the project. I sometimes wanted to research a topic in too much detail, mainly out of personal interest. I learned that details can be important but are time consuming and often are not the deciding factors in decision making. I think that scoping helps in limiting complexity as long as the necessary assumptions can be argued for. Personal or practical reasons can absolutely suffice in a project setting.

The last personal learning ambition I had was to gain experience making a design with the material as the starting point. I certainly gained experience here as I learned new methods of generating application ideas for a certain material. Overall, the approach to first understand the material by researching literature but at the same time start playing with the material, did suit me well. The ideation phase proved more challenging however. Idea generation was initially unstructured and my hope was that experts would come up with interesting ideas. I learned that a more structured and methodological approach gives more certainty for outcomes, is easier to plan with and generates more diverse ideas. During the idea selection phase however, I focused on structured methods too much and tried to use the weighted objective methods which is not possible with a large variety of non-detailed ideas. However, making a vision and some early requirements helped me effectively reduce the number of ideas. In the final selection I struggled with finding the right decision criteria. Here I could have trusted my expertise as a designer a bit more and used less rigorous methods from the start.

Lastly, scientific report writing should have been a learning goal. Throughout the project I realized that I still have a lot to improve in efficiently writing a scientific report. I learned a lot from the many helpful comments from my supervisors but am still struggling to write in a concise and structured manner.

To conclude, I think I became a more autonomous designer by doing this project on my own. I encountered difficulties but managed to overcome them, with some help from my supervisors. In the future I will be more confident in dealing with an explorative project and I will be able to make effective choices.

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Appendices

Appendix A: WTB Damage

Lightning strike damage

A lighting strike can severely damage a WTB both locally and globally. More than 88% of the strikes occur at the tip of the blade but the resulting shock wave and temperatures can also damage the blade towards the root such as delamination, debonding which can result in shell detachment and tip detachment. Amount, location and type of damage is strongly dependent on the material used which makes it hard to predict for TPC WTB's (Katsaprakakis, Papadakis, & Ntintakis, 2021). In general it can be assumed that mainly the tip is affected by lightning strikes.

Fatigue damage

Fatigue damage from fluctuating forces like wind gusts most likely occurs at the root section of the blade. Delamination and cracking are the most likely results and need an initial delamination or crack to propagate. This seed point is most likely caused by other damages such as lightning strikes or leading edge erosion.

Figure 1 Leading edge erosion

Leading edge erosion

Water droplets, salt crystals and other particles that impact the leading edge of the WTB well as UV-light and humidity or moisture can cause a decrease of efficiency of 5% (Katsaprakakis et al., 2021). More interesting for this thesis however, is the severe structural damage of the leading edge following the erosion which can in term also be the starting point of delamination or cracking by ice or fatigue loads (Figure). However mostly the tip area is affected as the velocity in this area is the highest (Slot, Gelinck, Rentrop, & Van der Heide, 2015).

Damage from icing

Depending on the environment, built up of ice on the blade decreases the turbine's efficiency. Ice can also cause delamination and cracking when entering the laminate while expending. Cyclic internal ice formation will quickly expand the delamination area. As an initial point of entry is necessary the leading edge is most likely to be damaged (Katsaprakakis et al., 2021).

Spanwise damage extent

It was found that for a 10MW wind turbine blade of 86.4m blade length the outer most 28% encounters precipitation erosion (Verma, Di Noi, Ren, Jiang, & Teuwen, 2021). When this same factor is applied to the 75m reference blade, the leading edge will encounter precipitation damage from roughly 54m up to the tip. Factors like rotation speed, location and droplet size influence this length but the 28% does give a valuable insight in the extent of the damage.

Sources:

Katsaprakakis, D. Al, Papadakis, N., & Ntintakis, I. (2021). A comprehensive analysis of wind turbine blade damage. *Energies*, *14*(18). https://doi.org/10.3390/en14185974

Slot, H. M., Gelinck, E. R. M., Rentrop, C., & Van der Heide, E. (2015). Leading edge erosion of coated wind turbine blades: Review of coating life models. *Renewable Energy*, *80*, 837–848. https://doi.org/10.1016/j.renene.2015.02.036

Verma, A. S., Di Noi, S., Ren, Z., Jiang, Z., & Teuwen, J. J. E. (2021). Minimum leading edge protection application length to combat rain-induced erosion of wind turbine blades. *Energies*, *14*(6). https://doi.org/10.3390/en14061629

Appendix B: Forming experiment 2 – Vacuum bag in oven

Goals

The goal of this experiment was to get acquainted with thermoforming using a vacuum bag while heating the whole stack in an oven. The secondary goal was to see if using this method would yield higher quality results than reshaping by hand. Higher quality is defined as less fibre buckling or kink bands forming.

Layup

2x [-45/45] Bi-axial non crimp 812 g/m^2. This laminate was made using the resin infusion process and yielded 1.2mm thick plates.

Process

Preparing the stack

First the composite panel was positioned over the mould in such a way that the fibres would be diagonally formed in a [-45/45] direction. Both moulds surface and panel were given a generous amount of MarboCote 227 CE release agent. Bits of tape were applied to stabilize the panel (figure 1). Next a layer of clear FEP foil was applied followed by a breather blanket to distribute the vacuum (figure 2). Bridges were made and vacuum foil was applied. Excess material from the bridges was pre-formed in order to provide enough material in the 90° transition area from mould to aluminium base plate. A quick leak check was performed. However in the end, a small leak was found after forming.

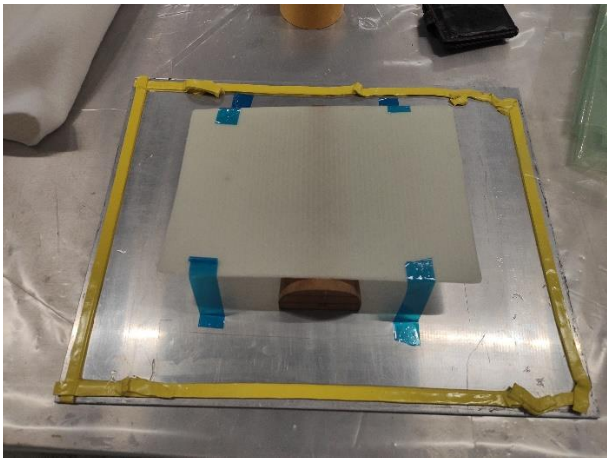
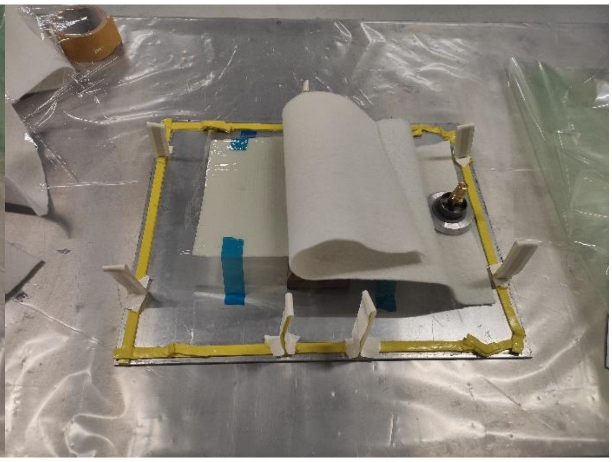


Figure 1: Glass/Elium panel suspended on the mould..



Figuur 2: Release foil, breather and vacuum coupling applied.

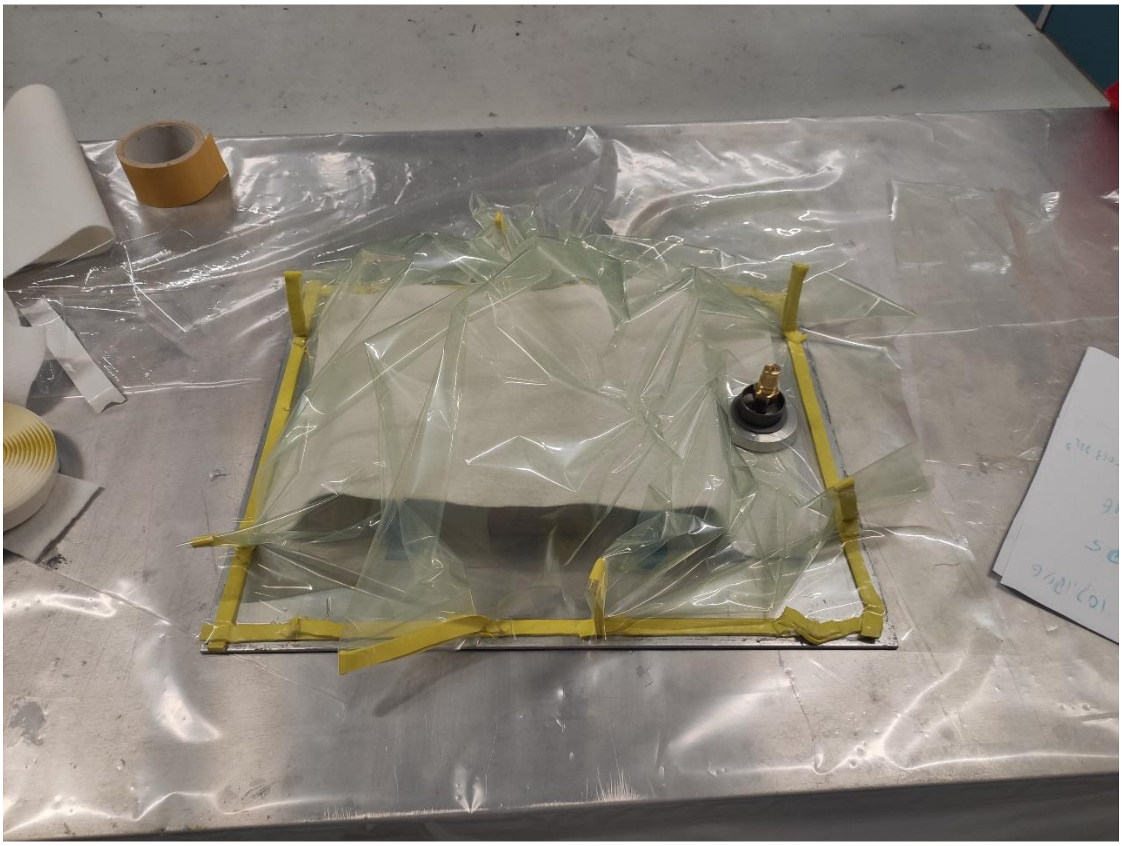


Figure 3: Vacuum bag applied, bridges pre-formed.

Forming

The stack was gradually heated to 190°C by putting it in the oven while the oven was warming up (figure 4). It took 40 minutes to reach the desired 190°C forming temperature provided by Arkema. It is assumed that in this 40 minutes the laminate did also warm up to 190°C. Now the vacuum was applied. It was planned to have a gradual decrease in pressure. However due to a mistake the vacuum was applied at a rapid rate. After the vacuum was applied for a brief time (not recorded), it was released again. Because of severe spring back, it was decided to re-apply the vacuum. Now it was decided to leave the vacuum for half an hour while the whole stack was kept at 190°C. During this time the initial pressure of 75mbar straight after application of vacuum gradually dropped to 60mBar. After half an hour the stack was removed from the oven and put on top of another aluminum plate to act as a heatsink (figure 5). This rapidly cooled down the stack and after 15 minutes the surface of the stack was warm to the touch, estimated 50°C. Now the vacuum was released and the formed panel was de-moulded. The thermal and pressure cycle can be seen in figure 6.

Figure 4: Stack in the oven and vacuum hose connected.

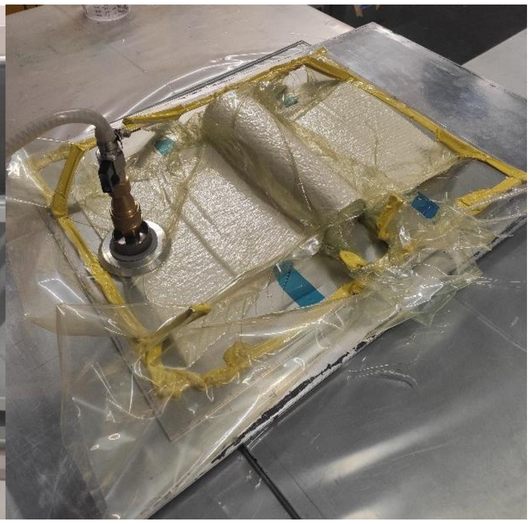


Figure 5: Stack after forming and cooling down.

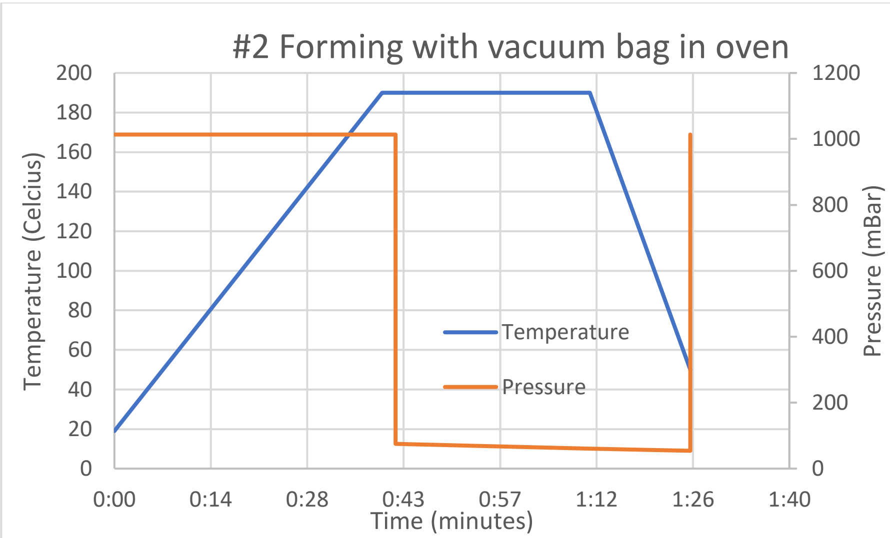


Figure 6: Temperature and pressure development over time

Results

After the shaped panel was removed from the vacuum bag it was visually inspected. A couple of defects are discussed below.

Shape conformity

The formed part conformed well to the positive 'convex' curvature of the mould. However the laminate did not reach into the 90° corner between mould and aluminium base plate. The reason for this could be the small leak discovered which prevented the vacuum pressure from approaching 0mBar. Friction between the aluminium base plate and the panel could also have contributed. Figure 7 shows the non-conformity of this lower corner.

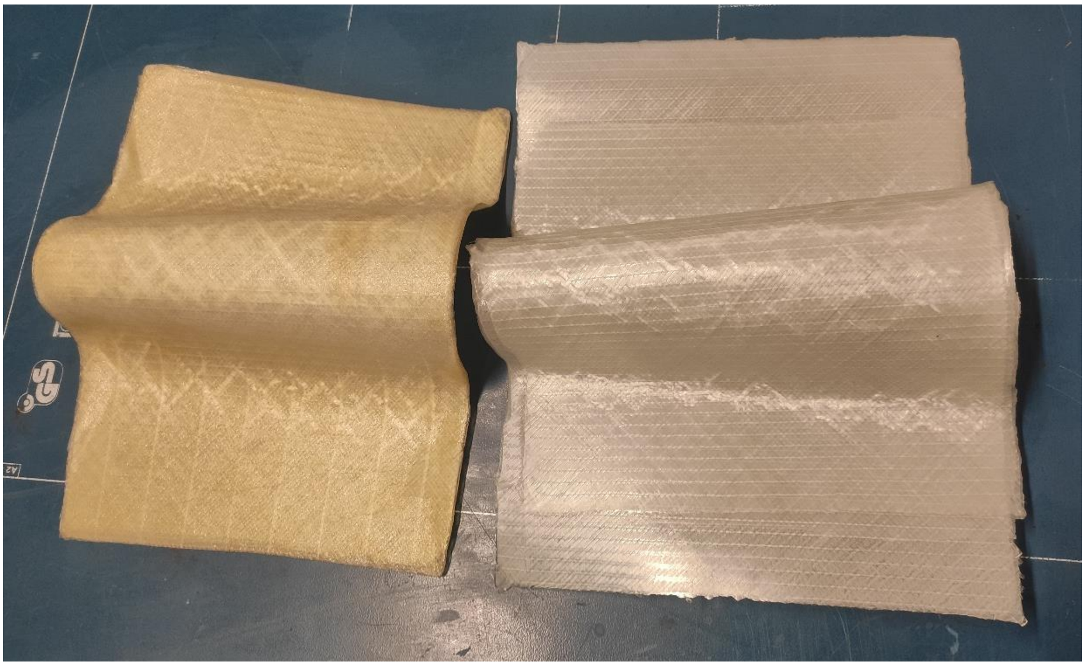
After de-moulding, the part started to twist. Possibly due to some residual stresses in the material caused by the heating cycle. This was also experienced with manufacturing of flat plates.

It is hypothesized that by keeping vacuum pressure on the laminate for longer, caused the matrix material to relax. This decreased internal stresses and by that reduced the spring back.

Figure 7: on the right the laminate can be seen 'bridging' the 90° corner

Colour

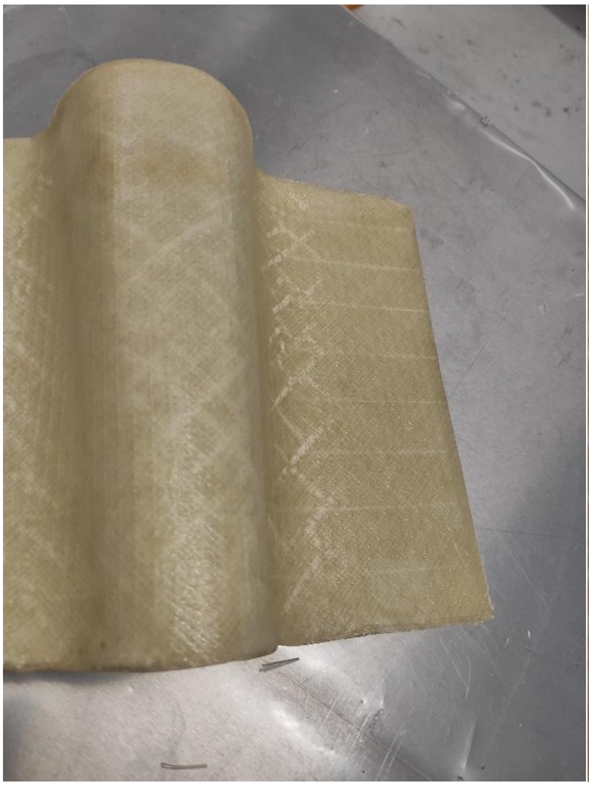
Surprisingly the colour of the part changed drastically from off white to a yellow/brown hue. This is assumed to be caused by some sort of chemical reaction initiated by the elevated temperatures. It is as of now (07-12-2022) unknown if this chemical reaction only causes visual changes in the material or that degradation is occurring. The latter could negatively impact the material properties and should therefore be avoided when possible. Figure 8 shows a comparison between a non-browned and a browned part. The manufacturer of the material should be asked for information on matrix degradation. It is hypothesized that the exposure time to elevated temperatures is the main affecting factor. This is based on the finding that short but intense heat (as used in the manual forming) did not change the colour, even though the plate was producing vapor due to temperatures being higher than 200°C.



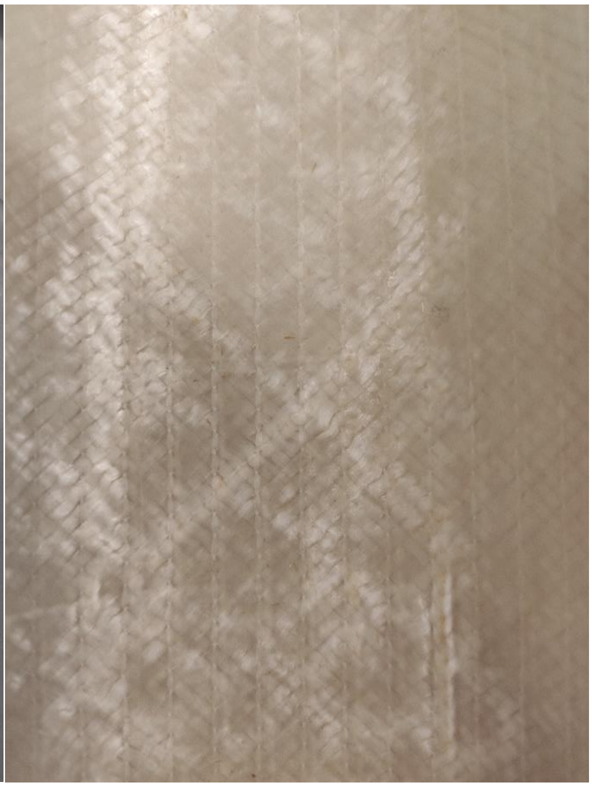
Figuur 8: Vacuum bag/oven formed part (left) and manual shaped part (right)

Buckling/ Dry spots

Again fibre buckling was observed although less pronounced than in the manual forming. Interesting is the pattern in which the fibres buckled. The lines of buckled fibres forming kinkbands are distributed in a repetitive and symmetrical cross shaped pattern. The reason for this pattern is likely the deformation mechanism of intro ply shear. Because of the local applied pressure the molten matrix system is partially squeezed out of the laminate leaving behind dry spots in this cross shaped pattern. Figure 9 shows the pattern of kink bands and dry spots. Figure 10 shows a closeup of one of the bands. Remark: buckling and waviness is sometimes hard to distinguish.



Figuur 9: kink band pattern



Figuur 10: kink band pattern closeup

Fibre waviness

Figure 1 shown a closeup of some fibre waviness identified. This waviness was discovered in the areas of buckling. Interesting is that waviness was more pronounced on the small radius side of the mould than the larger radius side.

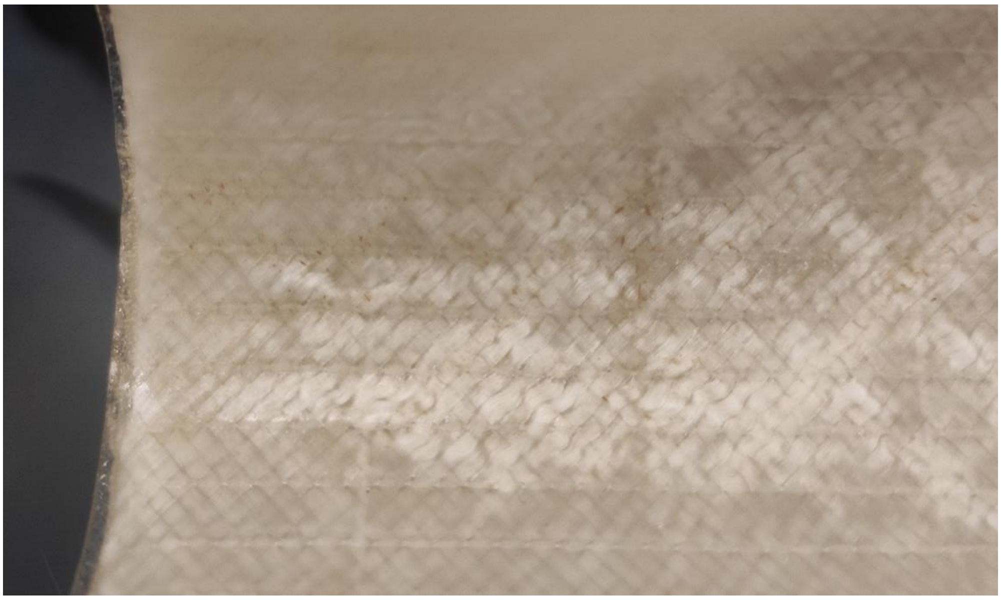
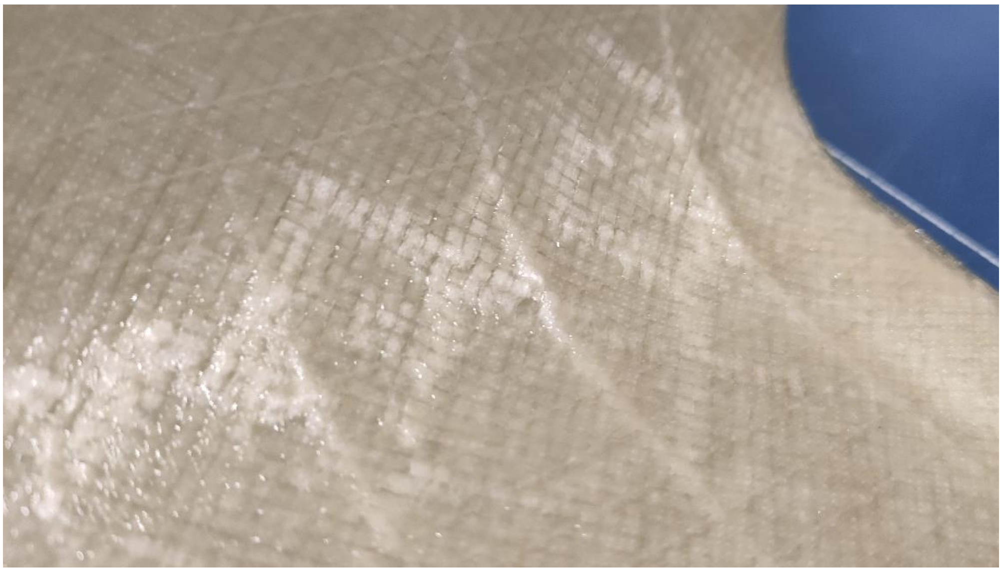


Figure 11: Closeup of fibre waviness.

Sagging

Figure 12 shows a close up of the laminate experiencing sagging. It is believed that his is caused by the stitching fibres resisting to conform to the mould shape, leaving a void underneath. Since vacuum pressure is applied, this open space will try to pull the fibres towards the mould. In a regular interval ridges are formed as the material in between sags down. These ridges however are not caused directly by the stitching but rather a 2 g/m^2 stabilizing layer within the Bi-ax fabric.



Figuur 12: 'ribs' forming as fibres are pressed to the mould while stitching is countering this movement.

Decompaction/deconsolidation

It is unsure if the laminate decompacted because measuring the thickness in areas prone to decompaction, experience noise due to the kinkbands and sagging. It is assumed that decompaction is likely but not as pronounced as say a laminate formed under high pressure (Joos press). This is due to the forming pressure being almost equal to the pressure of the original infusion process, even slightly lower (infusion at around 250mBar to prevent cooking of the matrix).

Conclusion/limitations

In general the result is believed to be of higher quality than the manual shaped specimen. However the goal of forming a part without fibre buckling or waviness is not reached. Also the colour change is concerning as this could mean degradation of the matrix material possibly leading to a decrease in mechanical properties of the whole laminate.

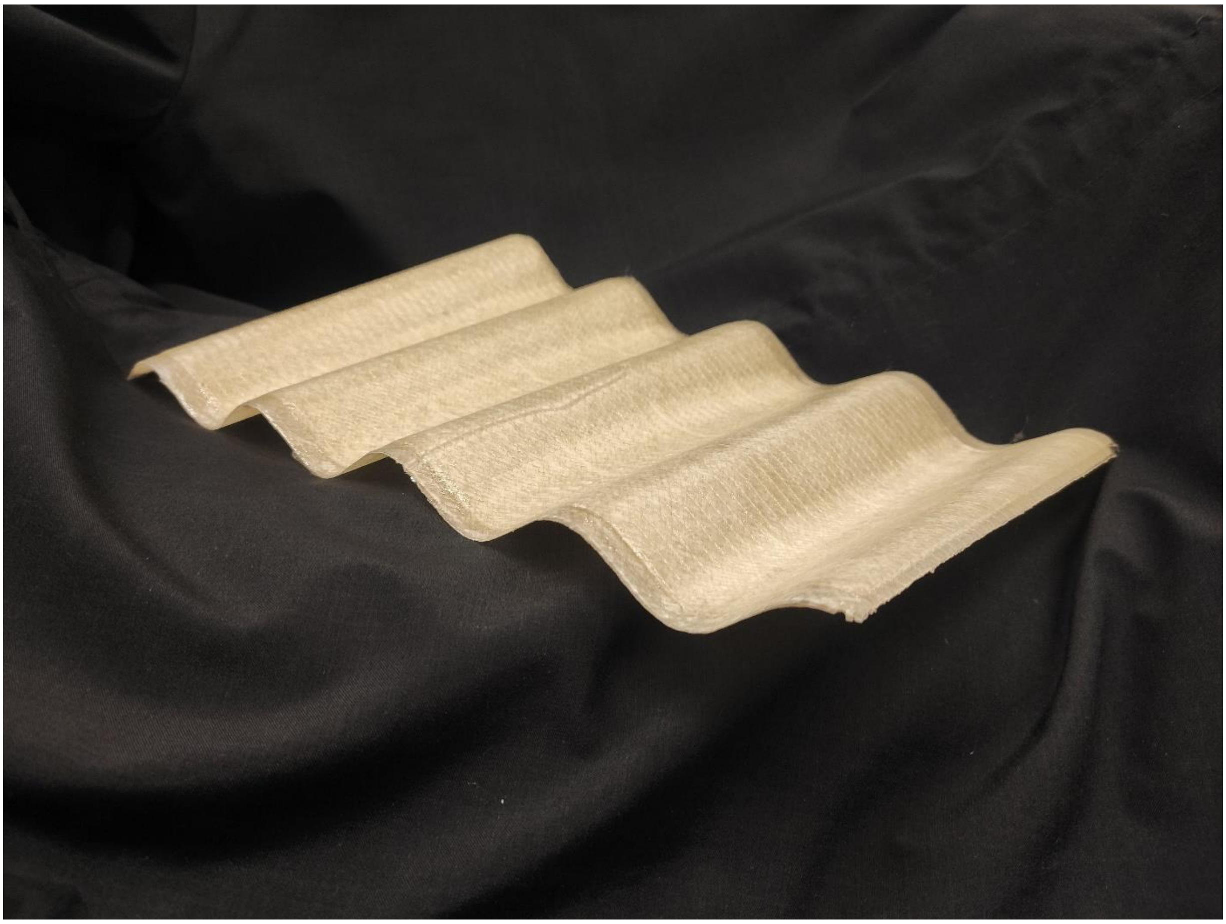
The most relevant limitation of this experiment is that the layup used is not the same as a representative TPC WTB layup. The WTB's use bi-axial and UD material while in this test two layers of [-45/45] of bi-axial material is used. The addition of the UD material will likely yield different results. Reason for not using UD material is that by the time of writing this report the material is not at hand.

Future work

In subsequent testing the following items should be addresses.

- Shorter exposure to elevated temperatures to reduce matrix colour changing/degradation by:
    - Pre-heat oven
    - Making use of thermocouples to check when laminate is at forming temperature
- Slower vacuum application to allow the plies to slip, possibly reducing buckling.
    - This is contradicting the aim of lowering exposure time
- Slower cooling rate to decrease buildup of residual stresses (Julie Teuwen: expert opinion)
    - Program oven for a temperature ramp down
- Better vacuum drop test to prevent leaks and improving shape conformity.
- Browned matrix should be checked for degradation.

Appendix C: Forming experiment 3 – Corrugated sheet



Goals
The goal of this experiment was to see if this material would be formed in a corrugated sheet shape to assess the feasibility of this re-use application Idea. A secondary goal was to minimize the browning of the laminate.

Layup
2x [-45/45] Bi-axial non crimp 812g/m^2. This laminate was made using the resin infusion process and yielded 1.2mm thick plates.

Process
Preparing the stack
First the composite panel was positioned over the mould in such a way that the fibres would be diagonally formed in a [-45/45] direction. The moulds surface was given a generous amount of MarboCote 227 CE release agent. Bits of tape were applied to prevent the panel from shifting. A thermocouple was taped on the laminate to track the temperature change of the laminate itself (Figure 1). Next a layer of clear FEP foil was applied followed by a breather blanket to distribute the vacuum. The vacuum bag was closed and the vacuum connection 'donut' applied (Figure 2). A quick leak check was performed.

Figure 6: Composite panel and thermocouple on the mould.

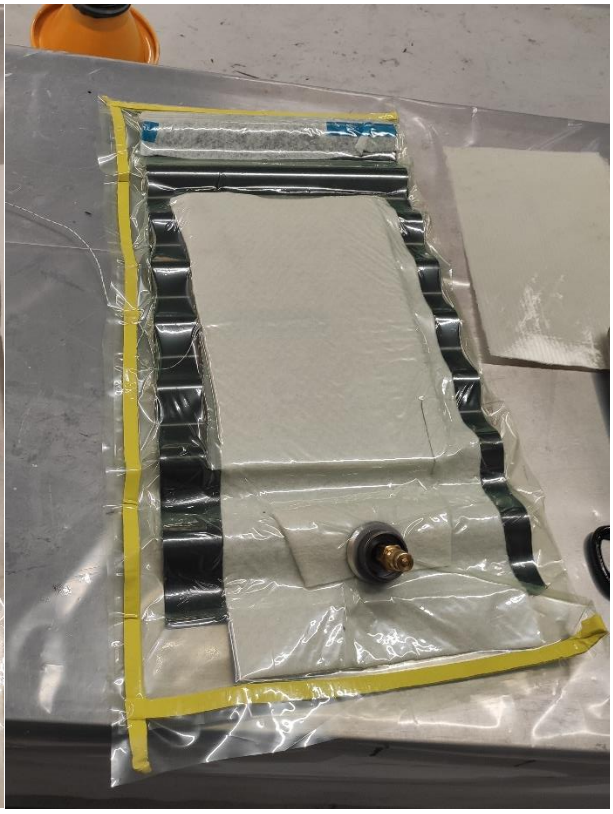


Figure 7: Vacuum bag closed and coupling 'donut' applied.

Forming
In this experiment, the laminate was warmed up as fast as possible in the oven to limit the exposure time. The oven was pre heated to 190° C after which the stack was put in the oven. The temperature of the laminate was tracked by reading and recording the temperature of the laminate

in constant intervals. The goal was to wait for the laminate to reach forming temperature of 180° C but the heating rate slowed down significantly after 150° C. It was therefore decided to start applying about 40% vacuum (600mbar) at a laminate temperature of 164° C after 10 minutes. When the temperature reached 175° C it was decided to apply full vacuum. The pressure was slowly decreased over a timespan of about 2 minutes until 10mBar. By this time the laminate reached 177 ° C. After 23 minutes, 6 minutes after application of full vacuum the laminate reached a temperature of 180.3° C. It was decided to now start cooling. A slow cooling rate of initially 1 degree per minute was chosen to try prevent internal tension in the material. Meanwhile the pressure was still decreasing slightly to 6mBar. When the laminate reached 67° C after 53 minutes it was decided to take it out of the oven for further cooling (figure 3). Interestingly the pressure started to rise slightly up to 16mBar when it was decided to release the vacuum. Buy this time the laminate temperature was 22° C. No significant springback was noted however After demoulding the part started to skew probably due to some asymmetrical thickness in the material (edges). The thermal and pressure cycle can be seen in figure 4.

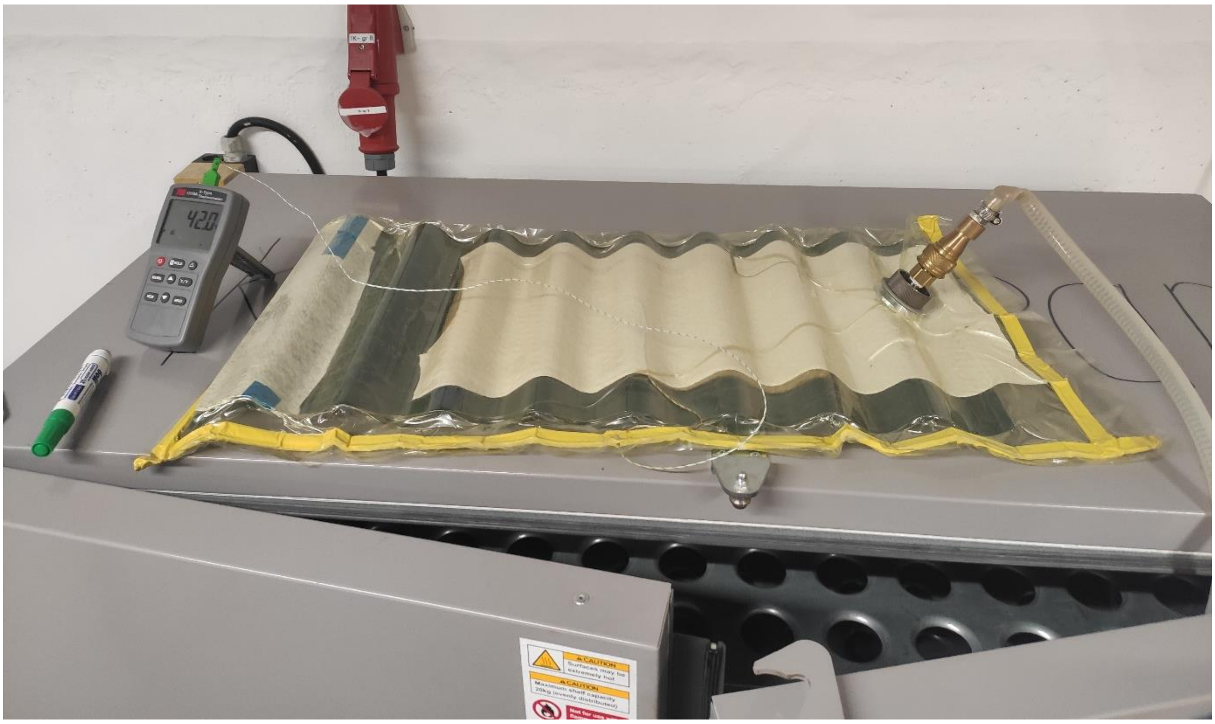


Figure 3: Stack on the oven while cooling, note the thermocouple showing the temperature.

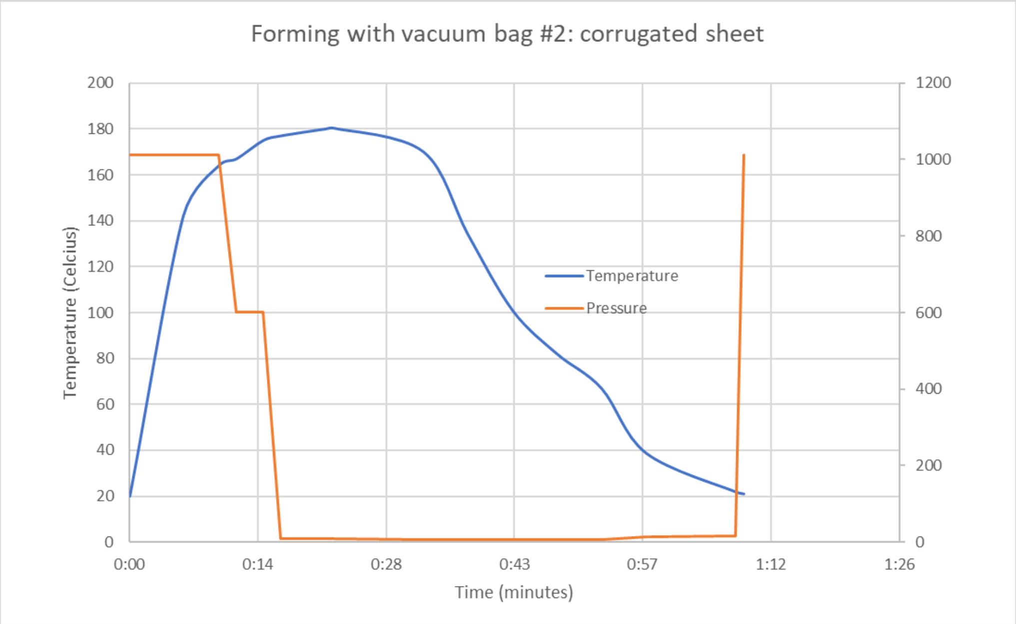


Figure 4: Temperature and pressure development over time

Results

After the shaped panel was removed from the vacuum bag it was visually inspected. A couple of aspects are discussed below.

Shape conformity

The formed part conformed well to the positive 'convex' curvature of the mould (figure 6). The concave shape was slightly bridged but only minor. This resulted in some rough areas on the part which can be seen in figure 6.

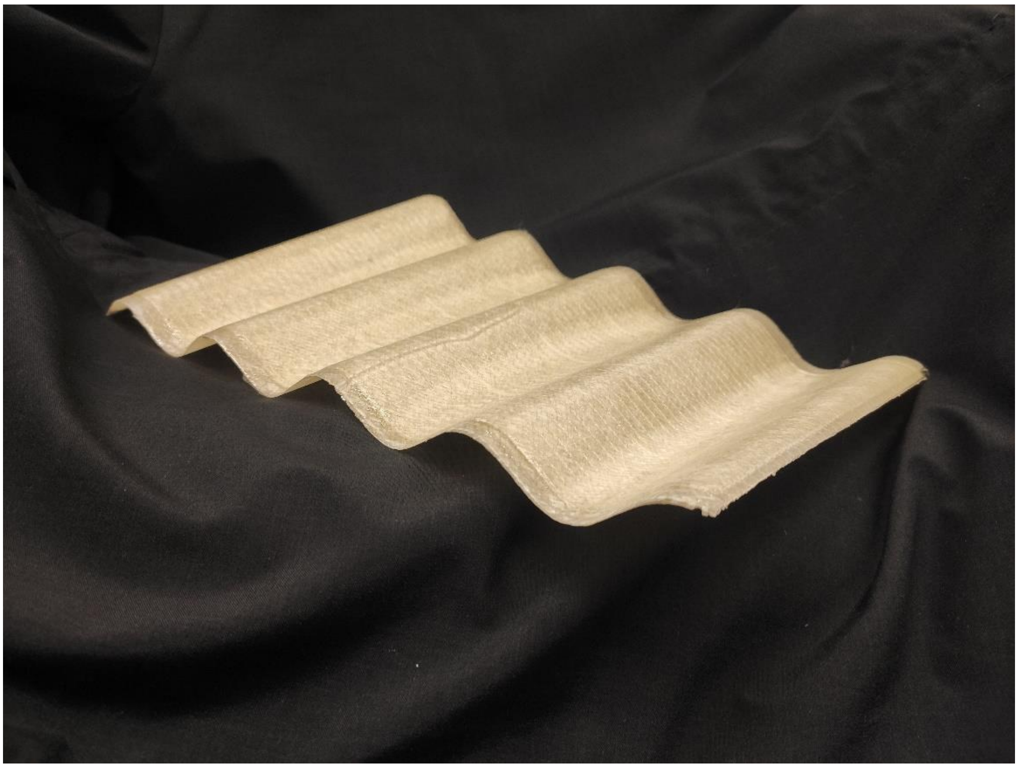


Figure 6: The formed corrugated sheet. Note the small wrinkle imprinted by the thermocouple.

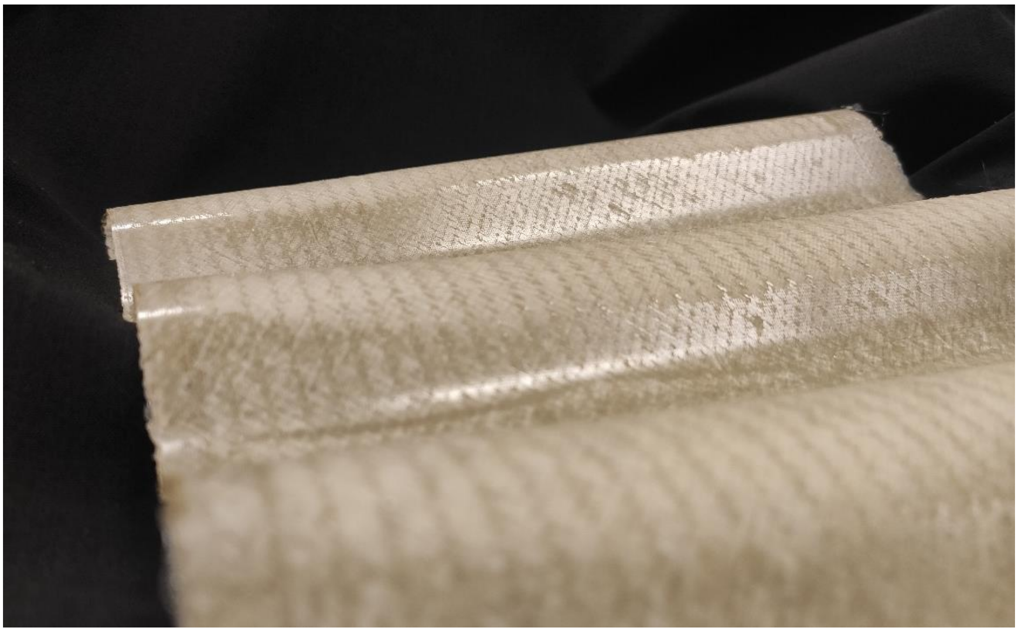


Figure 7: Rough areas in the part which did not touch the mould surface forming small matrix droplets.

Colour

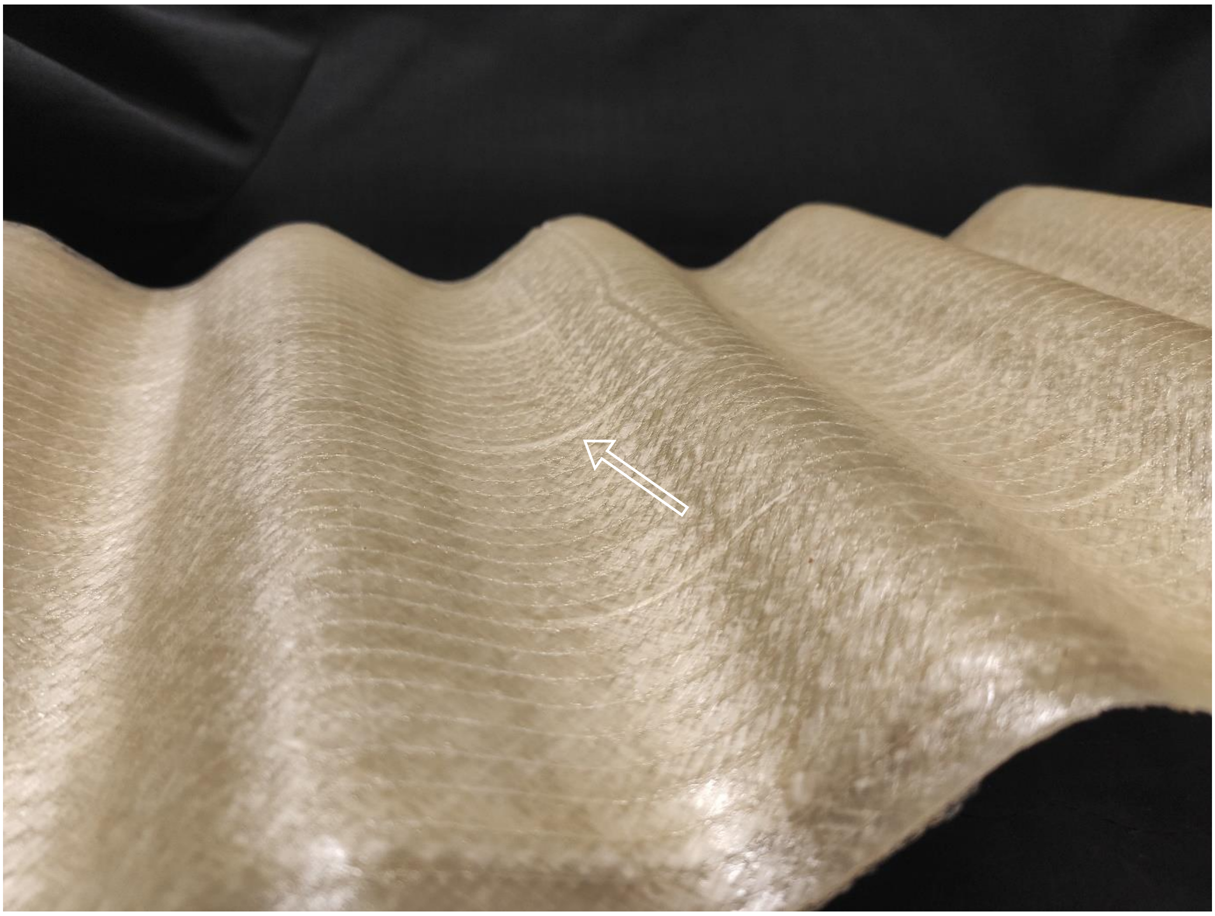
Again the colour of the part changed drastically from off white to a yellow/brown hue. This is assumed to be caused by some sort of chemical reaction initiated by the elevated temperatures. It is as of now (14-12-2022) unknown if this chemical reaction only causes visual changes in the material or that degradation is occurring. However Julie Teuwen expects it to be degradation or oxidation.

Buckling/ fibre waviness

No buckling or fiber waviness was found on the part.

Sagging

Figure 12 shows a close up of the laminate experiencing sagging. It is believed that his is caused by the stitching fibres resisting to conform to the concave mould shape, leaving an open space underneath called bridging. Since vacuum pressure is applied, this open space will try to pull the fibres towards the mould. In a regular interval ridges are formed as the material in between sags down. These ridges however are not caused directly by the stitching itself as the distance between them is approximately nine time larger than the distance between stitching lines. It should be noted that the sagging is less pronounced than in forming experiment #2 due to a smaller void between laminate and mould surface.



Figuur 12: 'ribs' forming as fibres are pressed to the mould while stitching is countering this movement.

Decompaction/deconsolidation

It is unsure if the laminate decompacted because measuring the thickness in areas prone to decompaction, experience noise due to the matrix being pulled out of the fibers forming small bubble like structures on the surface. It is assumed that decompaction is likely but not as pronounced as say a laminate formed under high pressure (Joos press). This is due to the forming pressure being almost equal to the pressure of the original infusion process, even slightly lower (infusion at around 250mBar to prevent cooking of the matrix).

Conclusion/limitations

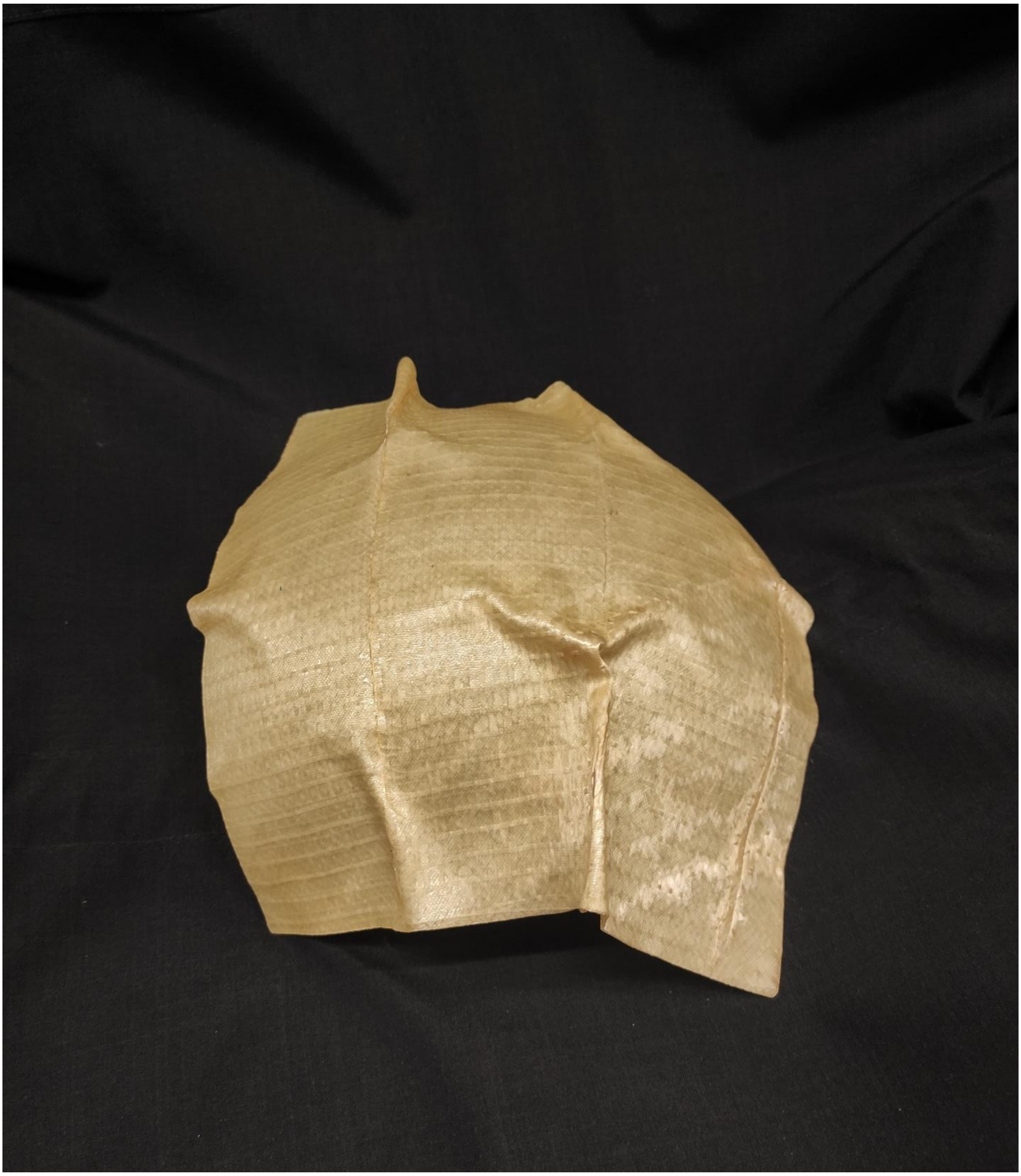
In general shape conformity is better than expected. It can be concluded that forming corrugated sheets with this layup should be possible as no buckling or waviness was found. However a limiting factor is that the layup used is not the same as the representative layup of UD and Bi-ax material. Another conclusion is that the laminate was still exposed too long to higher temperatures in oxygen rich environment, indicated by the browned matrix. This exposure time is mainly caused by the slow heating rate of the laminate. The use of a thermocouple caused this insights and it will therefore be used in later experiments as well. The ridges forming is a not well understood phenomena.

Future work

In subsequent testing the following items should be addresses.

- Shorten exposure to elevated temperatures to reduce matrix colour changing/degradation by either:
    - Heating the laminate in a different way than by convection
    - Applying vacuum earlier in the process
- Browned matrix should be checked for degradation.
- Forming with representative layup consisting of UD and Bi-ax material.

Appendix D - Forming experiment 4 – Dome shape



Goals

The goal of this experiment was twofold: To point out challenges in the process of forming of a double curved surface with a vacuum bag, and secondly to see how the material responds to a strongly double curved surface.

Layup

This is the first experiment with the simulated layup of a wind turbine blade comprising of: a Unidirectional 600g/m^2 layer made out of several 75mm wide strokes followed by a layer of [-45/45] Bi-axial non crimp 812g/m^2. Figure 1 shows the laminate with the directions of fibers. This laminate was made using the resin infusion process and yielded 1.1 mm thick plates. As can be seen the quality of the plates rather poor and the darker areas signal dry spots. However these dry spots are believed to have a small effect on the overall outcome of this experiment.

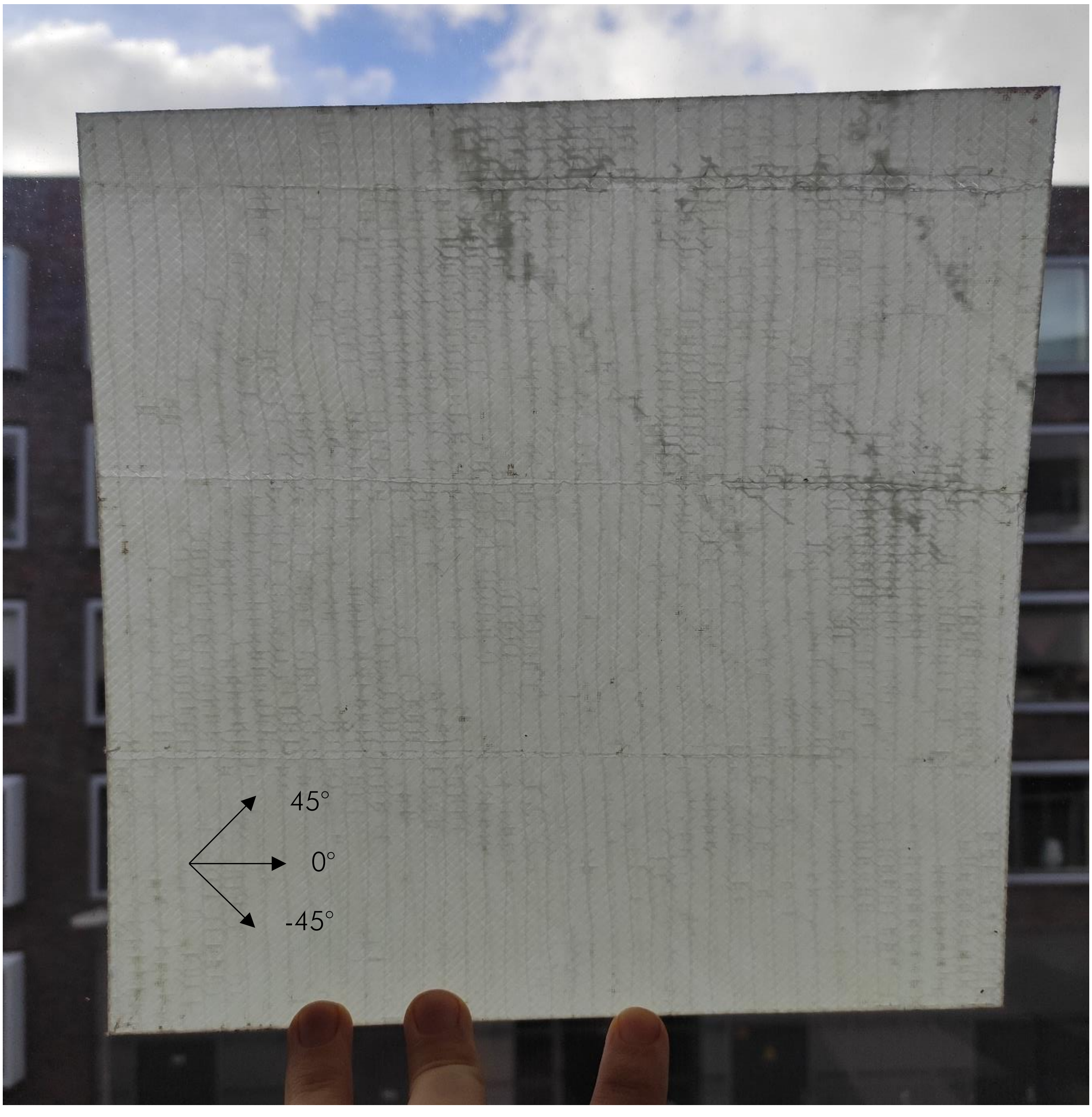


Figure 8: The composite panel with the direction of the fibers. Dark spots indicate areas without the proper amount of matrix material i.e. dry spots.

The mould

The mould used is a stainless steel bowl with a radius of 125mm (figure 2). This was selected as it was the largest radius found in a double curved surface mould at the vacuum forming machine at the faculty of industrial design engineering. Furthermore this is exactly the same diameter as the mould used in the forming experiments performed by Wolthuizen, Schuurman and Akkerman (Wolthuizen, Schuurman, & Akkerman, 2014). It was though that maybe the results could be compared. However the manufacturing technique (compression moulding) proved to provide such different results that this is not possible in the end.

Figure 2: The dome shaped mould

Process

Preparing the stack

First the composite panel was positioned over the mould, Unidirectional side up. The mould surface was given a generous amount of MarboCote 227 CE release agent. Bits of tape were applied to prevent the panel from shifting. A thermocouple was taped on the laminate to track the temperature change of the laminate itself. Next a layer of clear FEP foil was applied followed by a breather blanket to distribute the vacuum (figure 3). The vacuum bag was applied, bridges made to have excess material and the vacuum connection 'donut' applied. Figure 4 shows the whole stack ready to go in the oven.

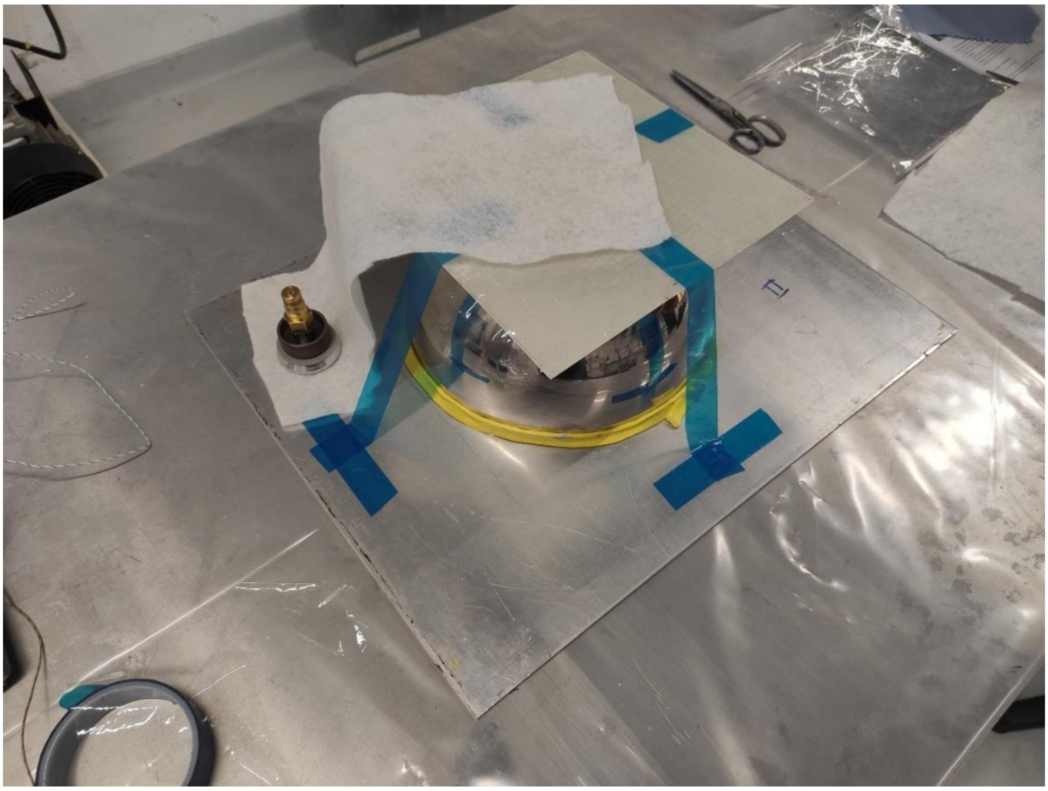


Figure 3: Mould, laminate, release foil and breather applied

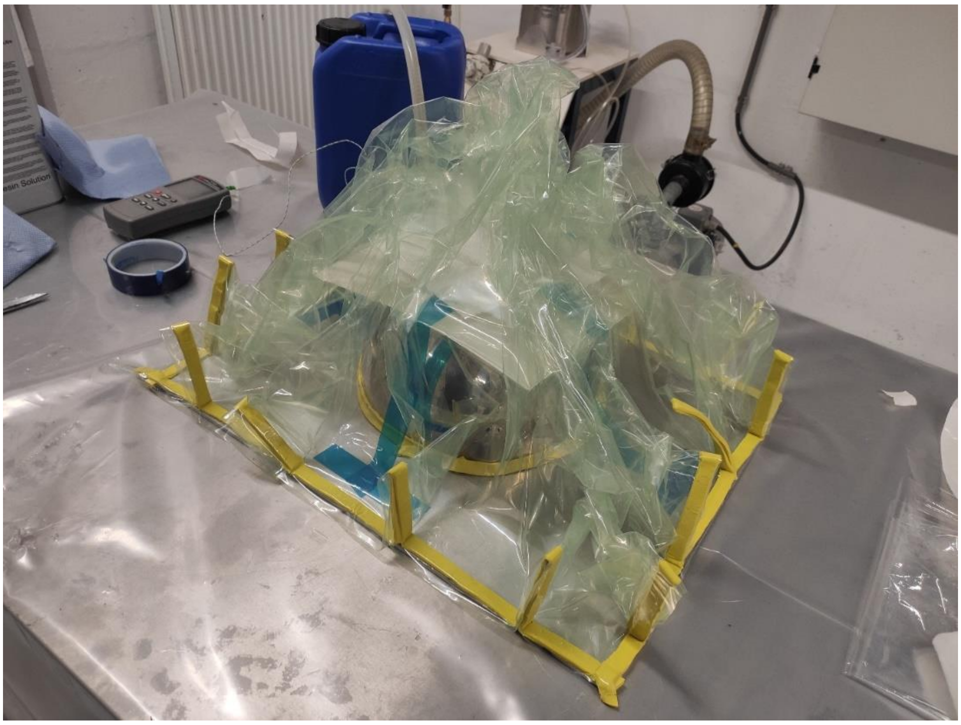


Figure 4: The complete stack. Notice the large amount of spare material by making the bridges.

Forming

The oven was pre heated to 195°C after which the stack was put in the oven. The temperature of the laminate was tracked by reading and recording the temperature of the laminate in constant intervals. The goal was to wait for the laminate to reach forming temperature of 180°C but a quick check showed the laminate to already be extremely weak at around 160°C. It was therefore decided to slowly start applying vacuum pressure at a laminate temperature of 167° C. Initially the pressure did not fall below 120mBar indicating some kind of leak. This is unfortunate as the full potential of the method was not tested. However in the end it would not have yielded much different results, maybe less or more pronounced. Interestingly the pressure slightly dropped after which can be seen in figure 7. After 15 minutes it was decided to start cooling the laminate. When the temperature reached 39°C the vacuum was released, no major spring back was recorded. Figure 5 shows the stack right after the cooldown and before

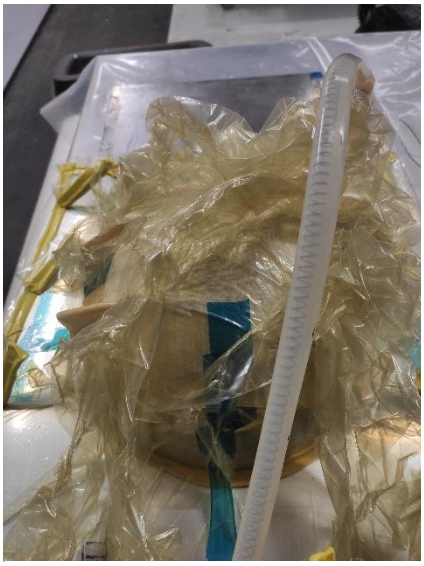


Figure 5: The stack while cooling down after forming

releasing of pressure. Unfortunately some vacuum bag material found its way under the laminate preventing the edges from touching the mould surface as can be seen in figure 6.

Figure 6: vacuum bag between the laminate and the mould surface

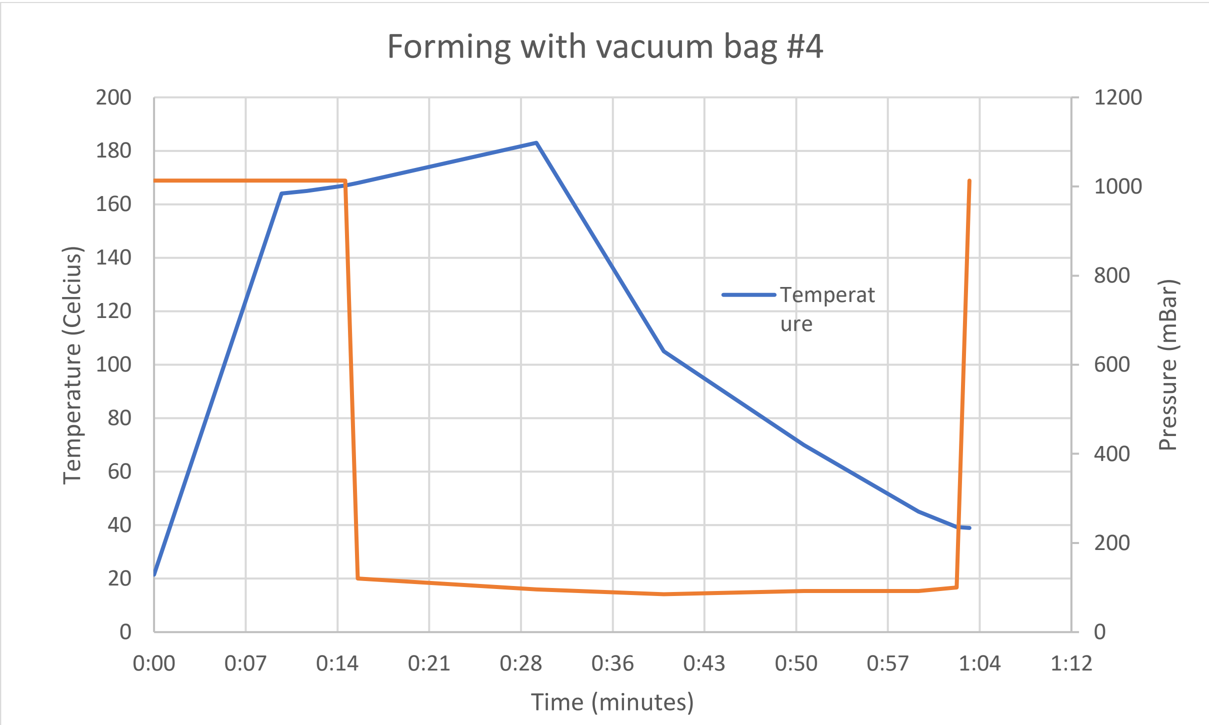


Figure 7: Temperature and pressure development over time

Results

After the shaped panel was removed from the vacuum bag it was visually inspected. A couple of aspects are discussed below.

Shape conformity and wrinkling

Even though there are areas that did conform to the dome shape, a lot of wrinkling can be seen as was expected. Good conforming areas are hard to convey by picture but by looking and feeling of the part these can be easily spotted. Figure 9 tries to show one of the well conforming areas. The wrinkles in Unidirectional fibre direction are located on the interface between the strokes of material. This makes sense as locally the laminate is weaker than its surroundings on these lines. In the 90° direction less wrinkling occurred, likely because the laminate is more resistant to deformation because of the UD fibres. The large wrinkles in 0° direction are probably cause by the ends of the laminate not only bending down but also being compressed towards each other by the vacuum bag without any support to prevent the folding. It is unsure what the reason is for the 0° wrinkling's to split in diagonal wrinkles . However it is likely that these are wrinkles in 90° direction (perpendicular to the UD fibres) which propagated after and from the 0° wrinkles. First the weakest area is folding, which is the are between strokes of UD, followed by the more resistant areas.

Figure 8: The result showing heavy wrinkling, look for the surfaces that are actually well shaped.

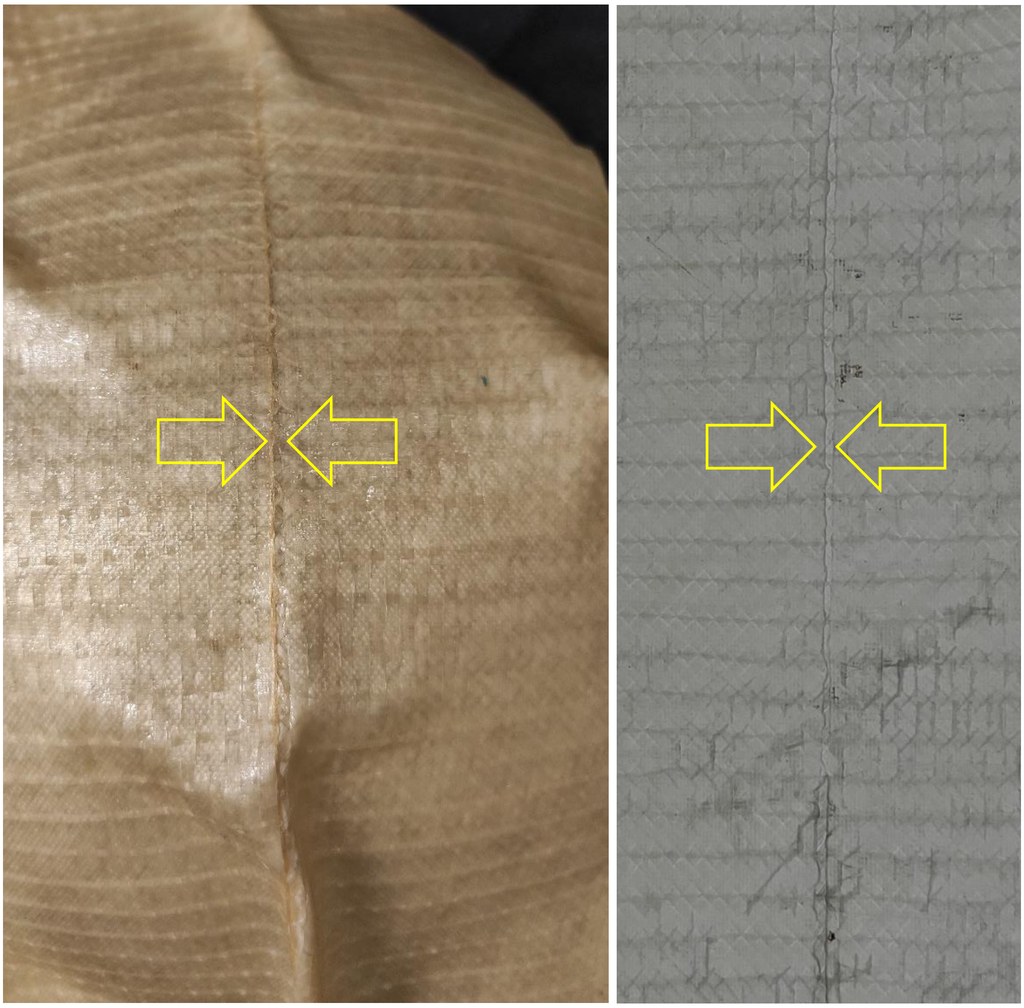
Colour

Again the colour of the part changed drastically from off white to a yellow/brown hue. In degradation test #1- oxidation this was found to be the first degradation step of PMMA and likely not dependent on oxygen.

Figure 9: Detail of the result showing the material can conform to the shape

Ply slip

At first glance it looks like quite some ply slip can be seen at the markes spot in figure 10. However this is not the case as the distance between UD strips is visually the same as before. Also the edges of the laminate do not look 'stepped' which could be an indicator that plies shifted in relation to each other. As some spots had good shape conformity, ply slip should occur but is not visualy notable.



Figuur 10: Distance between bands of UD material after (left) and before (right) shaping showing no significant changes.

Decompaction/deconsolidation

Some compaction at the edges of material was found as in this area the material was not pressed against the mould leaving room for the material to 'expand' in thickness. 1.3-1.4mm was measured where the original laminate has a thickness of 1.1mm

Conclusion/limitations

Even though the conclusion of this experiment is that with vacuum bag forming this type of curvature is too much, some areas showed promising results. This indicates that a larger radius mould should likely yield positive results. Furthermore it was discovered that the laminate is weak enough at 167°C which might open the possibility to shape the parts at temperatures lower than the temperatures causing degradation of the Elium matrix. Clearly an important limitation is the production process itself.

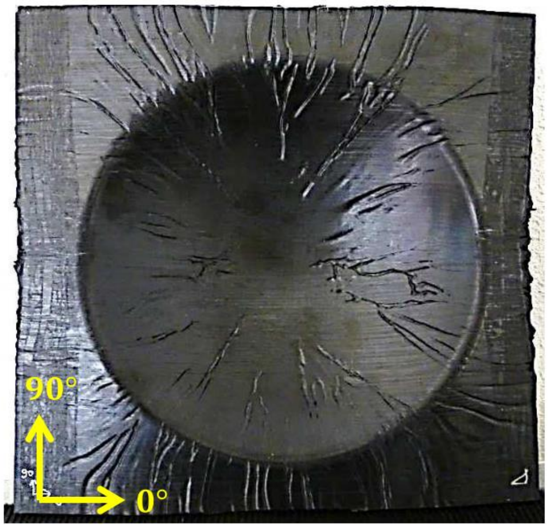


Figure 11: Carbon UD and PEKK formed by compression moulding showing wrinkling (Wolthuizen et al., 2014)

Future work

In subsequent testing the following options are interesting to experiment upon:

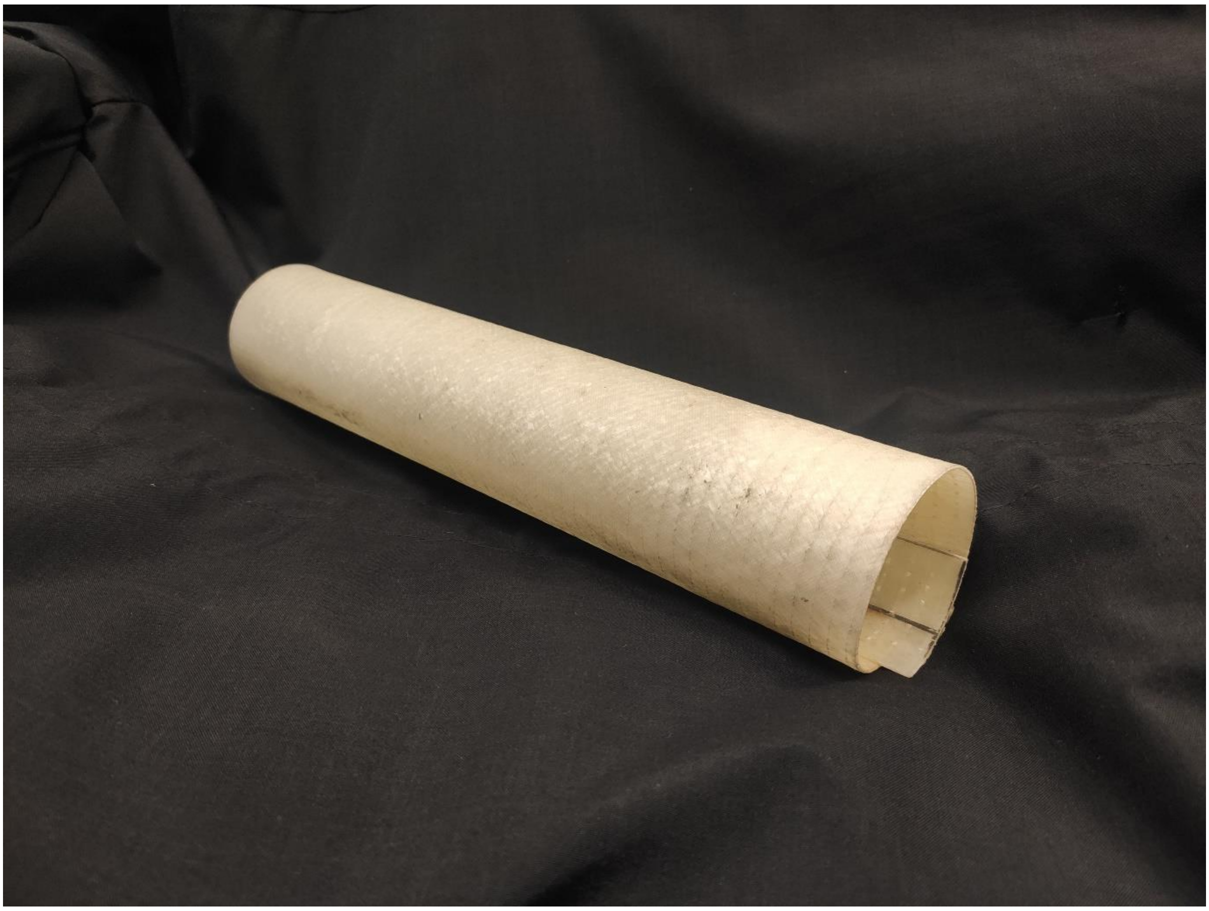
- Lower forming temperatures (maybe try as low as 150°C)
- Same dome shaped mould but adding a sheet of silicone to try reduce wrinkling
- Same dome shaped mould but stretching the bag over it to prevent wrinkling of the bag and therefore the part.
- Same dome shaped mould but matching the shape with another dome, simulating matched die forming.
- Larger radius double curved surface mould to try and establish the 'limit'

As Wolthuizen showed, even with compression moulding the unidirectional fibers will cause wrinkling which can be seen in figure 11 (Wolthuizen et al., 2014). It is therefore decided to increase the diameter of the double curved surface for the next experiments.

Sources

Wolthuizen, D. J., Schuurman, J., & Akkerman, R. (2014). Forming limits of thermoplastic composites. *Key Engineering Materials*, *611–612*, 407–414. https://doi.org/10.4028/www.scientific.net/KEM.611-612.407

Appendix E - Forming experiment 5 – Tube rolling



Goals
The goal of this experiment was to asses if shaping the material with a radius of 60mm would cause defects. Besides this the setup and process of this experiment was tested. Also the hypothesis that forming below 170-180°C decreases browning formed in forming study 4, was tested.

Laminate
Unidirectional 600g/m^2 layer made out of several 75mm wide strokes followed by a layer of [-45/45] Bi-axial non crimp 812g/m^2. Figure 1 shows the laminate with the directions of fibers and rolling direction. The Unidirectional layers are touching the mould, Biaxial on the outside. This laminate was made using the resin infusion process and yielded 1.1 mm thick plates. The plate was slightly curved as it originated from the leading edge section of the wind turbine section mould.

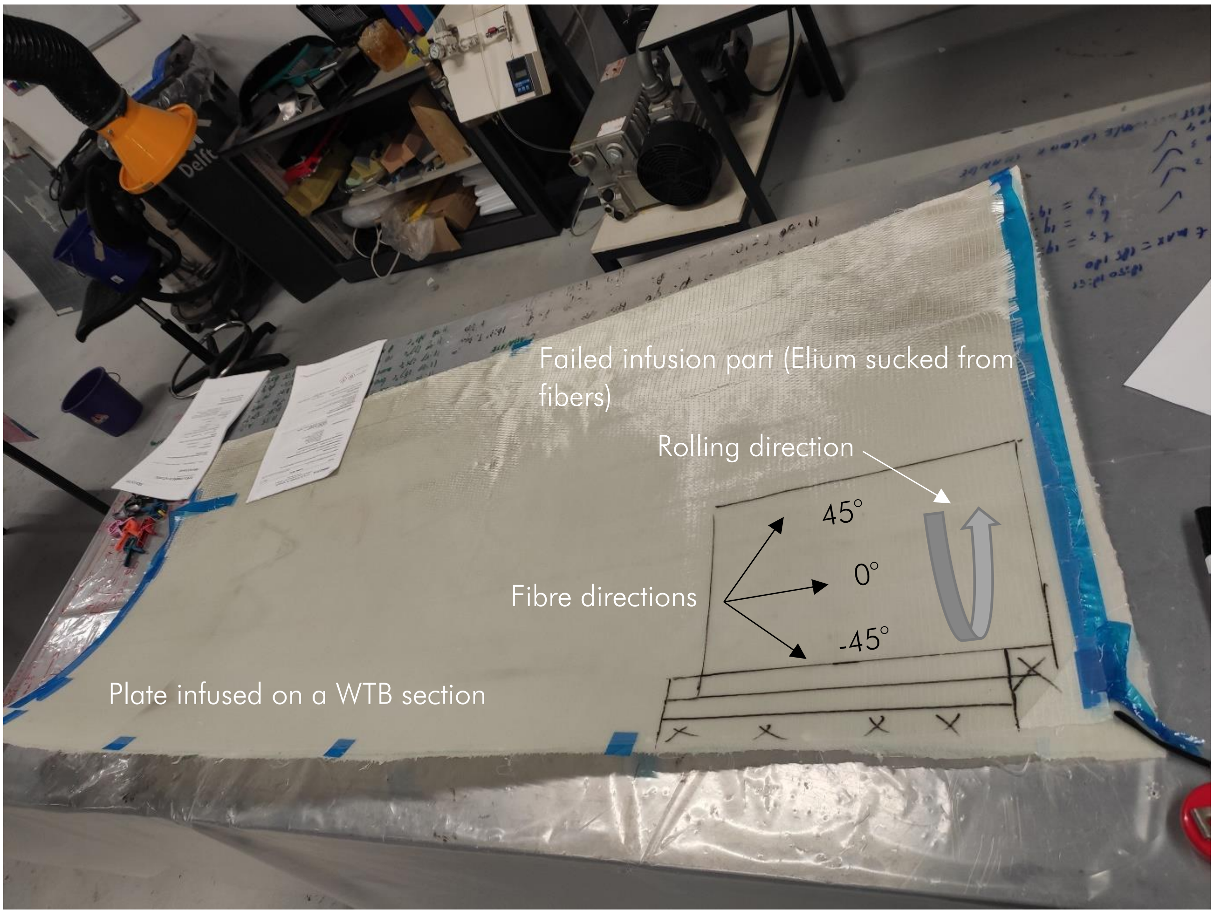


Figure 1: partially failed infusion showing the laminate to be formed.

Process
Contrary to the previous experiment I decided to not use the vacuum bag method. Instead the material was formed by hand assisted by clamping.

The mould
An aluminium tube with a diameter om 60mm was chosen as the mould because this is the minimum radius of lampposts.

The setup

Three heatguns were used to apply heat to the laminate. One heating the mould and by that heating the laminate by conduction to forming temperature. The other two heatguns were aimed on the laminate on the area just before the mould. These heatguns were placed in a holder which is fitted to a flexible arm to adjust the height. The laminate was taped to the mould with flashbreaker 2 tape which can resist temperatures up to 210°C (see Figure 3). On the other end the laminate was clamped to the table in order to provide backpressure while rolling to ensure good shape conformity and prevent defects like buckling. The setup can be seen in Figure 2. To measure the temperatures both an infrared camera and thermometer were used (Figure 4).

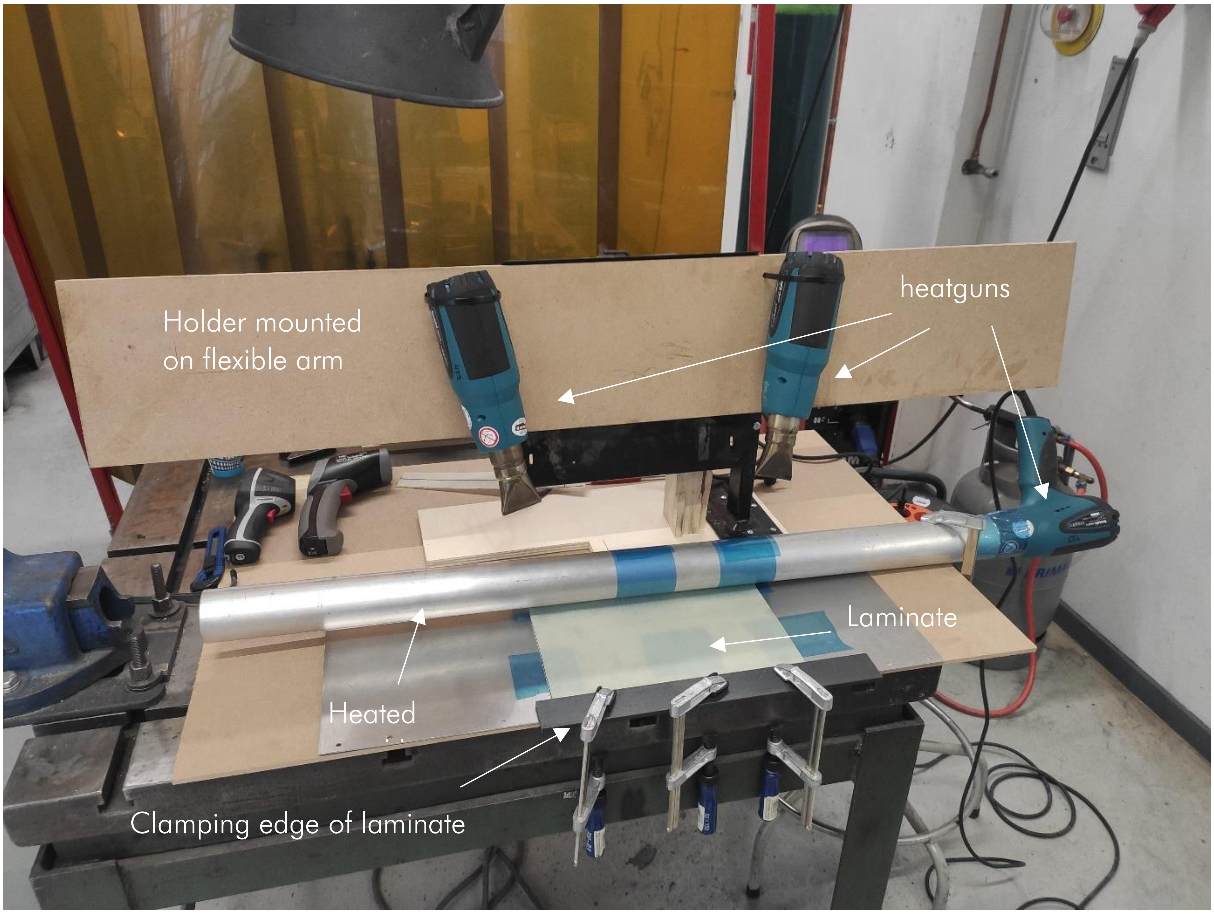


Figure 2: The forming setup.

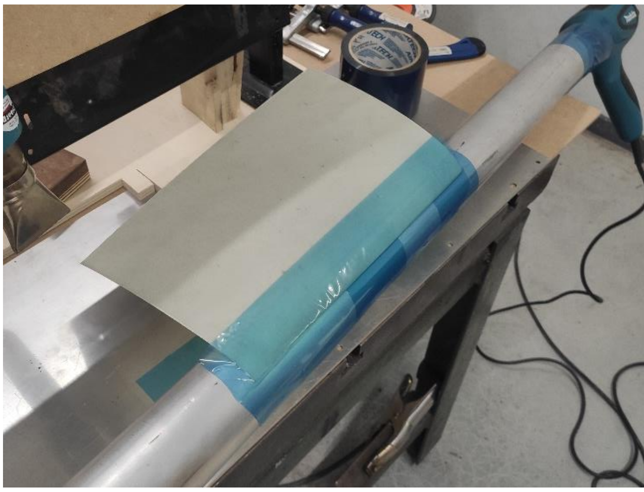


Figure 3: Laminate taped to the tube

Figure 4: infrared camera and thermometer.

Forming

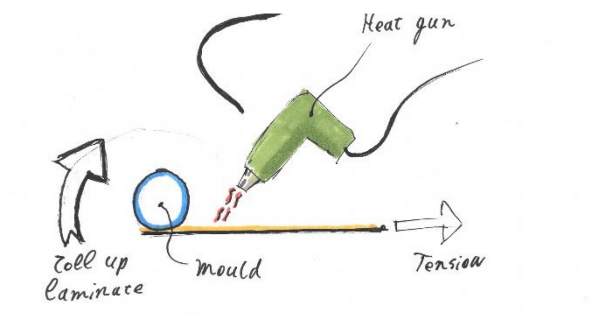
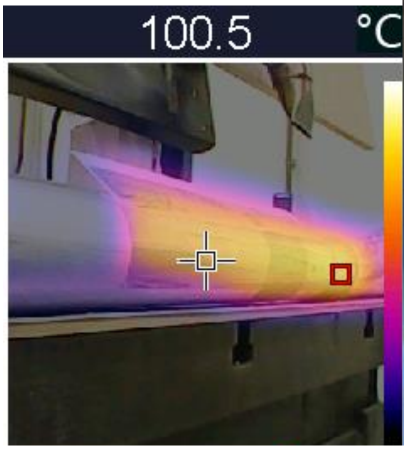


Figure 5: Sketch of the rolling process

Figure 5 shows a sketch of the forming process. The forming process started by heating up the mould to approximately 190°C. St first lower temperatures were aimed for but looking at the infrared camera it was quickly discovered that the temperature gradient over the mould was worse than expected as can be seen in Figure 6 . Therefore the temperatures needed to be increased to make sure that the laminate would be heated above melting temperatures. In the meantime the two 'convexion heatguns' were started and quickly warmed the laminate to approximately 150°C, however not as evenly as hoped (see Figure 7). To counter this the heat guns were shifted from left to right. When temperature readings aimed at the mould showed above 140°C at the colder side of the laminate, the rolling process started. Applying pressure horizontally to 'stretch' the laminate I started rolling towards the clamps. A peer student kept reading temperatures of the laminate and the mould to ensure everything stayed above roughly 140°C which proved to be the temperature at which forming the laminate was successful. To be sure, 150°C was aimed for (Figure 8). At the end of rolling I discovered that, logically, the last part of the laminate couldn't be rolled onto the tube as it was clamped down. The clamping was removed and the



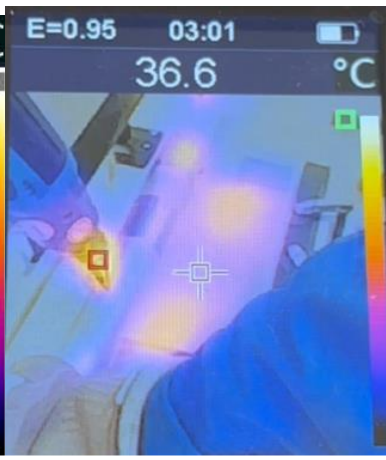


Figure 6: Temperature gradient

Figure 7: uneven heating of the laminate

Figure 8: measurement of the laminate

laminate further rolled onto the tube. Now the tube was clamped down in such a way that this last piece of material was pressed on the mould surface. After the tube and laminate cooled down to room temperature the tube was demoulded.

Results

In general the result of this experiment were positive. The process proved to be not too difficult and temperatures could be kept above 140°C for all parts. The only part of the process that needs rework is the uniform heating of the tubular mould. Besides that better insulating gloves should be used. As far as the ability of the laminate to form in the tube shape, results are generally positive as well. These results are described in the following paragraphs.

Shape conformity

The laminate conformed to the mould shape well approaching a circular cross section as can be seen in Figure 9. After demoulding the laminate however quickly twisted as internal stress had build up in the material. This however proved advantageous as now a near perfect butt joint formed (Figure 10).

Figure 9

Figure 10

Colour

Interestingly the laminate did not brown as much as in previous experiments. Figure 11 shows from front to back: virgin laminate, forming experiment 4 and forming experiment 5. It can be clearly seen that forming study 4 experienced significantly more browning than 5. This is likely caused by the decreased forming temperatures as predicted in forming study 4. This finding is further backed by the fact that more browning can be seen on the hotter side of the heated tube which reached temperatures over 160°C.

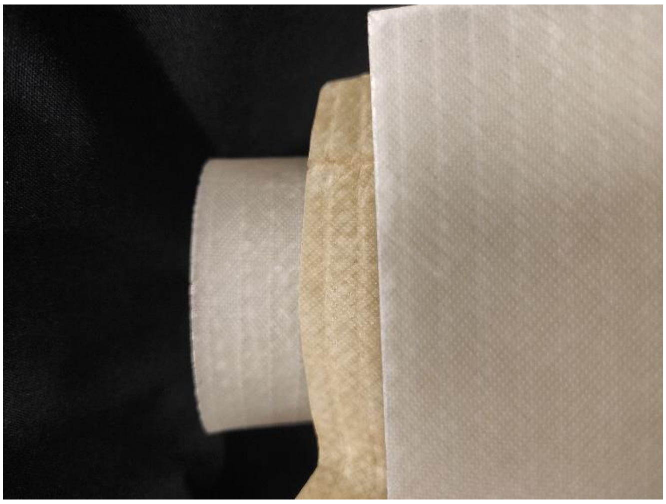


Figure 11: from left to right the formed tube, dome shape and virgin laminate showing the difference in colouring

Decompaction/deconsolidation

No increase in thickness could be measured, suggesting that no decompaction occurred.

"Speckles"

In figure 12 white speckles can be seen distributed over the surface of the pipe. As of now it is unsure what the causes and/or implications are. Possibly this is the fibre to matrix interface which is failing but this has to be checked by an expert. The waviness that can be seen in the picture is a result of the infusion process rather than the reshaping as this was spotted on the virgin laminate.

Figure 12: white "speckles"on the tube surface

Closing the section

To close the section a glue strip was formed in the same setup (figure 13). This strip was glued on the inside of the tube with thickened ELium by adding cotton flox. The result is a stiff tube which can be seen in figure 14.

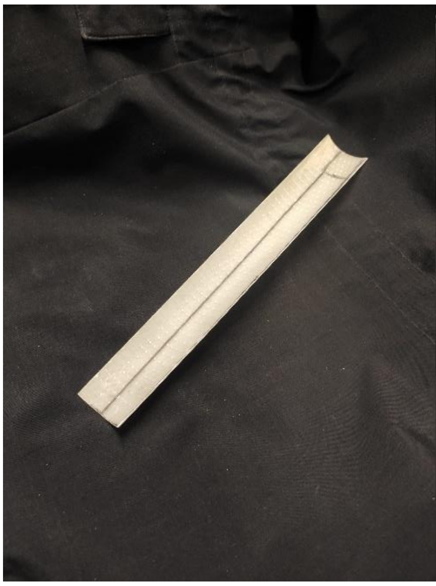


Figure 13: glue strip

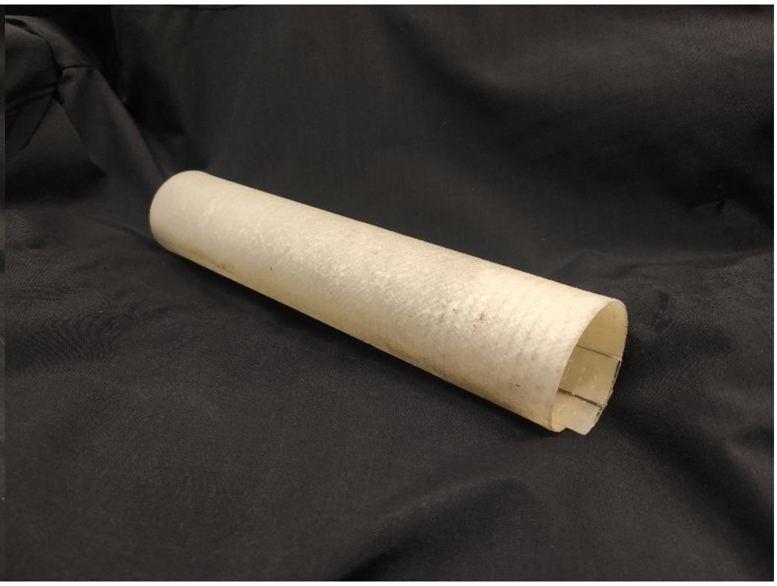


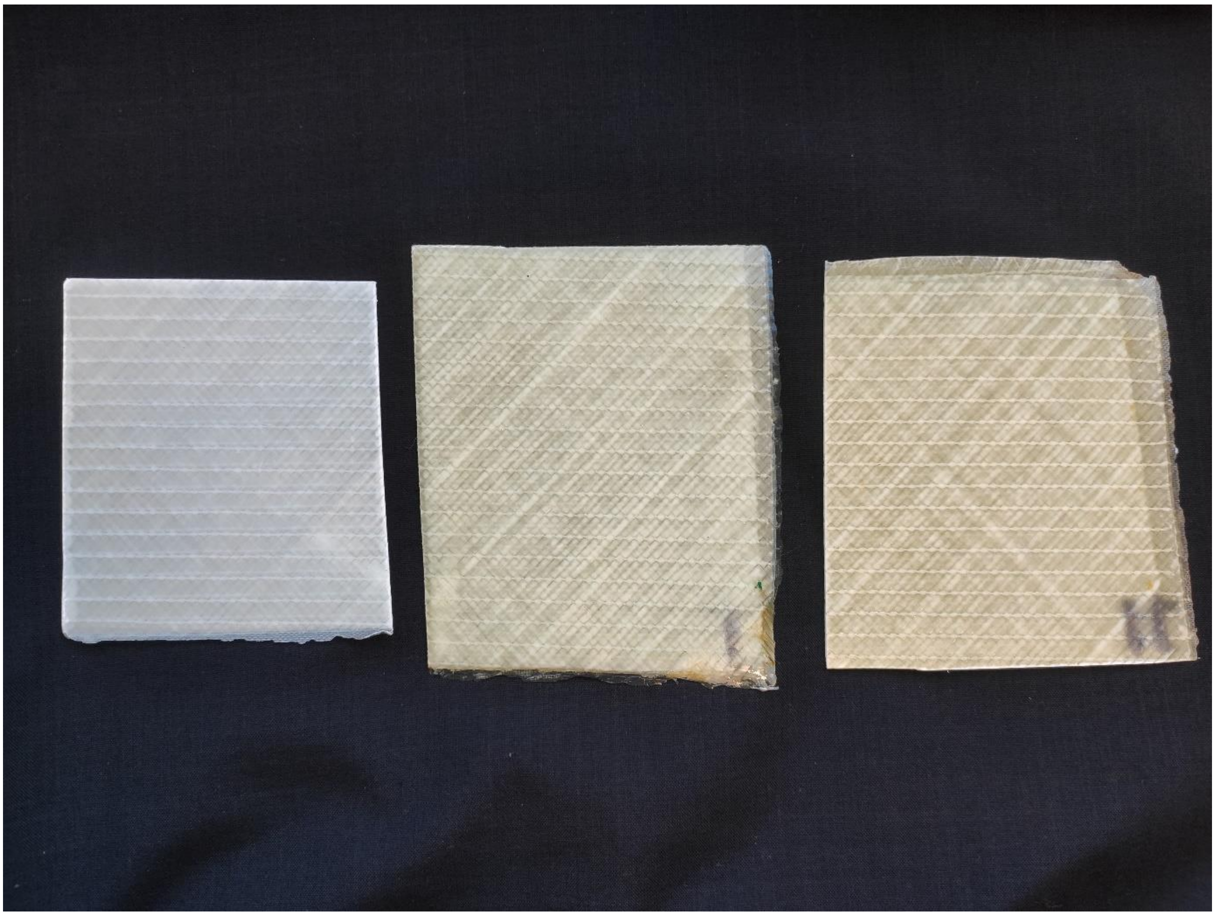
Figure 14: The completed tube

Conclusion/future work

In general it can be concluded that all three goals of the experiment are positively verified. The process produces relatively good quality tubes, the material can conform to the radius and browning was largely avoided. What should be checked is the implication of the white speckles forming on the surface of the tube. Other remarks for future experimenting with this setup are:

- More heat resistant gloves for a more comfortable shaping
- Longer laminate to avoid the need to unclamp the laminate
- More uniform mould temperature to avoid uneven heating of the laminate

Appendix F - Degradation experiment 1 – Oxygen rich and oxygen poor heating



Context/Goals

The goal of this experiment was to asses if oxidation would be the governing factor in the colour changing of ELIUM resin at prolonged exposure to the forming temperature of 180 degrees. This colour change was noted in forming experiments 2 and 3 and raised concerns if the browning signals degradation of the matrix. This degradation could change the mechanical properties of the laminate. It is important to know to what extent the properties of the material change by the reshaping process as this directly influences re-use applications. In literature it was found that most PMMA variations degrade in two steps: between 180-350°C and 250-400°C (Nikolaidis & Achilias, 2018). The first step is most interesting since these temperatures slightly overlap with the forming temperatures. In this experiment it was superficially assessed if the absence of oxygen by applying a vacuum would delay this degradation step.

Layup

2x [-45/45] Bi-axial non crimp 812g/m^2. This laminate was made using the resin infusion process and yielded 1.2mm thick plates.

Process

Preparing the plate

Two smaller samples of laminate were cut from a larger plate and weighed before being placed on an aluminium plate which received a generous amount of MarboCote 227 CE release agent. One sample was covered by a release foil and vacuum bag and air was evacuated. In figure 1 the two samples can be seen prior to heating.

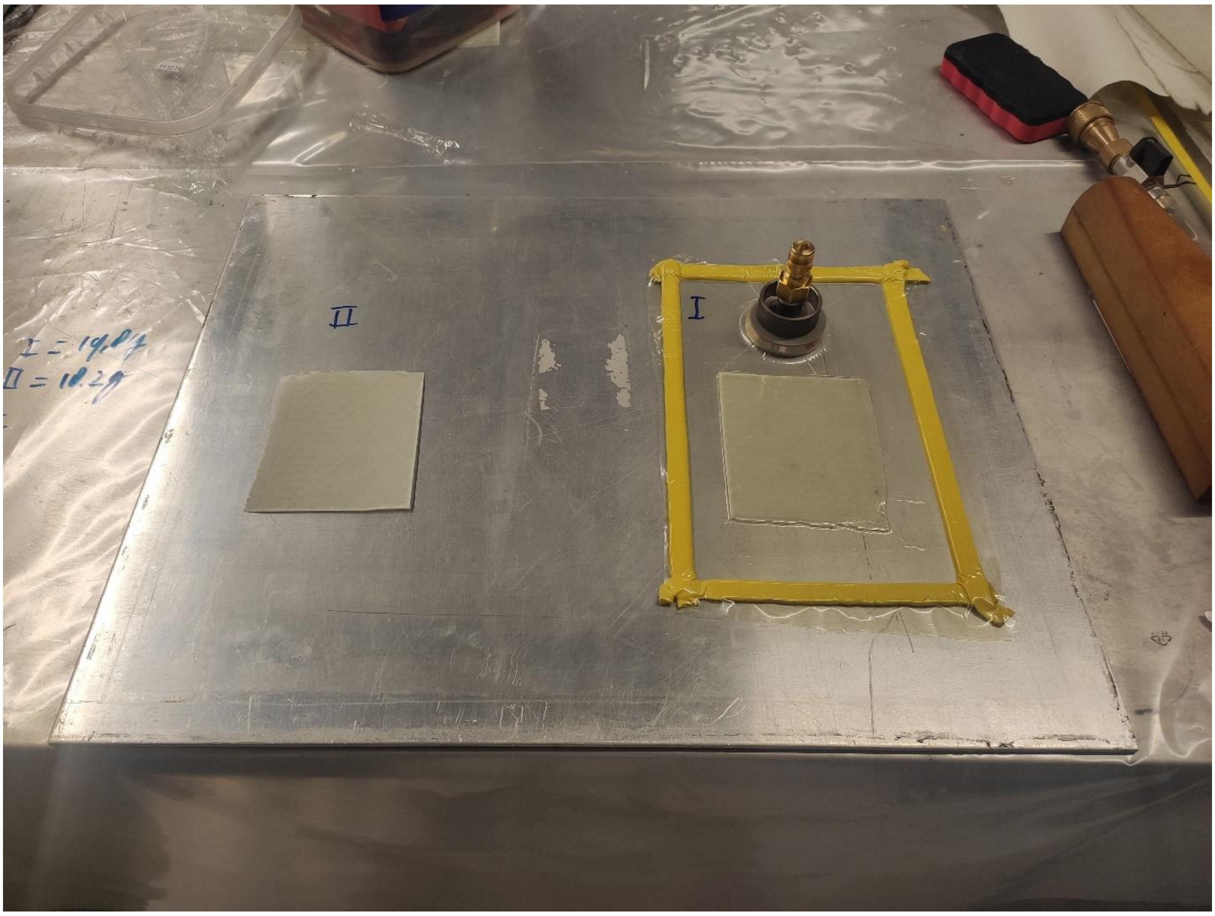
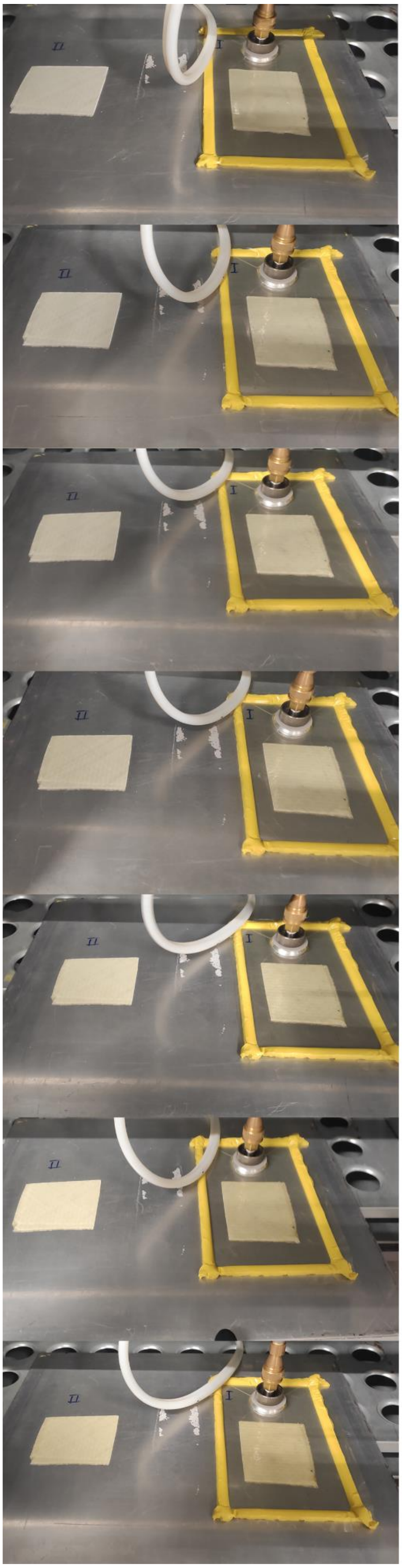


Figure 9: Composite panel and thermocouple on the mould.

Heating

The test plate was put in a preheated oven (180°C) and vacuum hose was applied. No thermocouple was used to track the temperature of the laminates. Every 5 minutes after the initial start of heating a photo was taken to track he colour changing. The sequence of photos can be seen in Figure 2. After heating the laminates were cooled down over a course of approximately half an hour.



T=5min

T=10 min

T=15 min

T=20 min

T=25 min

T=30 min

T=35 min

Figure 2: Browning of panels over time

Results

In Figure 3 the final result can be seen showing a non-heated sample, the sample heated under vacuum and the sample exposed to the air while heating. Interestingly no noticeable difference can be seen between the latter two samples indicating that air does not strongly influence at least the visual properties. It is suspected that also the degradation is not affected by oxygen. This means for the forming process that the applying a vacuum as soon as possible is probably not necessary.

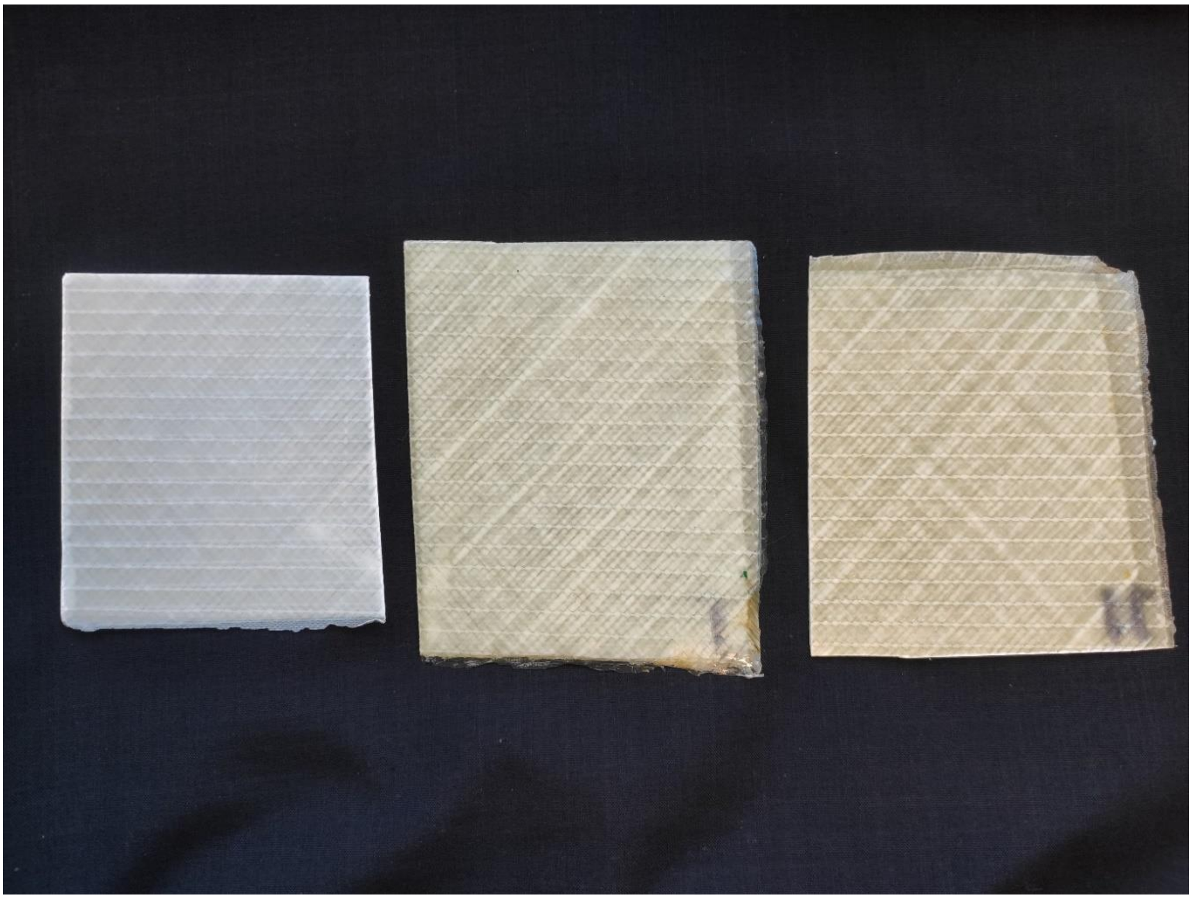


Figure 3: Ffrom left to right: non-heated, heated under vacuum and heated under normal atmosphere samples.

Future work

Because no literature was found describing the relation between the described first degradation step and mechanical properties either:

- Mechanical test have to be performed with browned and non-browned samples or;
- The possible change in mechanical properties has to be considered out of scope

Another possible step could be to:

- Try the shaping process at lower temperatures to prevent degradation

Sources

Nikolaidis, A. K., & Achilias, D. S. (2018). Thermal degradation kinetics and viscoelastic behavior of poly(methyl methacrylate)/ organomodified montmorillonite nanocomposites prepared via in situ bulk radical polymerization. *Polymers*, *10*(5). https://doi.org/10.3390/polym10050491

Appendix G - Estimating laminates mechanical properties

Mechanical properties of interest

Compressive and tensile strength are important properties which dictate at what load a structure fails. Most materials have a higher compression strength than tensile this is however not the case for most composites. This is why not only tensile strength but also compressive strength is taken into account. Since glass/Elium is not a ductile material the yield strength is not taken into account.

Estimating UD properties

Granta EduPack synthesizer was used to estimate the mechanical properties of a UD laminate of E-glass reinforced Elium. A material profile was made for Elium based on regular cast sheet PMMA and values provided by Arkema were used to substitute some important properties. These values can be seen in Table 1. The resulting material profile was used as input for the synthesizer. For the fiber material E-glass was chosen and a fibre volume fraction of 50% was assumed. The resulting mechanical properties can be seen in Figure 1.

Table 21

Shore D hardness	85 – 90		ISO 868
Coefficient of linear expansion	0.065	mm/m/°C	ISO 2155-1
Fracture toughness stress intensity, K_{IC}	1.2	MPa.m^{0,5}	ISO 13586
Elongation at break	2.8	%	ISO 527
Flexural strength	111	MPa	ISO 178
Flexural modulus	2.91	GPa	ISO 178
Tensile strength	66	MPa	ISO 527
Tensile modulus	3.17	GPa	ISO 527
Compression strength	116	MPa	ISO 14126
Compression modulus	3.83	GPa	ISO 14126

ELium / E glass (Unidirectional Composite) - 50%vf

Datasheet view: All attributes | Show/Hide | Find Similar

My records > Synthesized > Composites (Simple Bounds) > ELium > Unidirectional fiber > E glass >

Physical properties

Density	1,87e3	-	1,9e3	kg/m^3

Mechanical properties

Young's modulus	3,76e10	-	4,41e10	Pa
Yield strength (elastic limit)	9,79e8	-	1,06e9	Pa
Tensile strength	9,83e8	-	1,06e9	Pa
Compressive strength	8,09e8	-	8,92e8	Pa
Flexural modulus	3,76e10	-	4,41e10	Pa
Flexural strength (modulus of rupture)	8,09e8	-	8,92e8	Pa
Shear modulus	1,81e9	-	2,48e9	Pa
Bulk modulus	7,85e9	-	8,32e9	Pa
Poisson's ratio	0,288	-	0,303	

Thermal properties

Thermal conductivity	0,685	-	0,8	W/m.°C
Specific heat capacity	984	-	1,04e3	J/kg.°C
Thermal expansion coefficient	7,79e-6	-	1,17e-5	strain/°C

Electrical properties

Electrical resistivity	1,94e14	-	1,94e15	ohm.m
Dielectric constant (relative permittivity)	4,67	-	4,87	
Dissipation factor (dielectric loss tangent)	0,0255	-	0,032	

Primary production energy, CO2 and water

Embodied energy, primary production (virgin grade)	5,37e7	-	5,95e7	J/kg
CO2 footprint, primary production (virgin grade)	3,45	-	3,81	kg/kg

Notes

Source records
Matrix = ELium 188
Fiber = Glass, E grade (0.4-12 micron monofilament, f)

Figure 75

Effect of fibre orientation on properties

From literature I found an estimation for the degrading tensile strength caused by the orientation. In one study, experiments were performed with the goal of assessing the effect of fiber orientation on the mechanical behavior of woven E-glass/Epoxy composites (Seshaiah & Vijaya Kumar Reddy, 2018). It is assumed that a woven [±45°] ply experiences the same reduction in properties as a [±45°] Bi-axial layer. Table 2 to 4 shows the result of this study for tensile, compression and flexural properties. By rotating the fibers 45° a knockdown of about 89% for ultimate tensile strength and 68% for compressive can be expected. For the Young's (tensile) modulus a reduction of 37% was measured. Assuming the similar mechanical characteristics of Elium/glass and Epoxy/glass laminates, these factors can be used to determine the contribution of the biaxial layer [±45°] to the composites tensile strength which is later used in the pole strength calculation.

Table 22

Sample	Density g/cm³	Fibre volume (V_f%)	Composite Thickness (mm)	Load at Break (KN)	Ultimate Tensile Strength (MPa)	Tensile Modulus (GPa)	Yield strength (MPa)
$[0°]_s$	2.54	56.3 ± 2.1	2.97	54.97 ± 5.31	747.86 ± 10.12	14.23 ± 8.16	483.27 ± 6.11
$[90°]_s$	2.54	56.4 ± 2.3	2.99	8.93 ± 2.33	187.67 ± 6.54	5.53 ± 3.42	91.85 ± 5.23
$[0°/90°]_s$	2.62	57.8 ± 2.3	2.98	14.89 ±.6.11	283.54 ±.8.32	7.17 ± 7.14	183.24 ± 8.01
[45°/45°]	2.62	57.6 ± 2.1	2.99	4.07±1.34	81.84 ± 2.31	7.01 ±.2.11	33.79 ±1.33

Table 23

Sample	Density (g/cm³)	Fibre Volume (%)	Composite Thickness (Mm)	Max Compressive Load (KN)	Compressive Strength (Mpa)	Compressive Modulus (Gpa)
$[0°]_s$	2.54	56.3 ± 2.1	3.01	0.96 ± 0.05	14.65 ± 5.12	15.27 ± 0.41
$[90°]_s$	2.54	56.3 ± 2.3	3..02	0.63 ± 0.03	10.32 ± 3.34	6.87 ± 0.32
$[0°/90°]_s$	2.62	57.8 ± 2.2	3.02	0. 93 ±.0.04	12.45 ± 4.02	9.16 ± 0.71
[{45°/45°]	2.62	57.6 ± 2.3	3.03	0.27 ±0.07	4.64 ± 2.13	6.65 ± 0.23

Table 24

Sample	Density g/cm³	Fibre Content (Vol %)	Composite Thickness (mm)	Max Flexural Load (KN)	Flexural Strength (MPa)	Flexural Modulus (GPa)
$[0°]_s$	2.54	56.3 ± 2.1	6.01	0.84 ± 0.15	129.74 ± 12.2	9.62 ± 0.81
$[90°]_s$	2.54	56.4 ± 2.3	6..02	0.27 ± 0.01	64.82 ± 2.65	4.71 ± 0.56
$[0°/90°]_s$	2.62	57.8 ± 2.2	6.02	0.43 ±.0.04	84.25 ± 8.12	8.43 ± 0.72
[45°/45°]	2.62	57.6± 2.1	6.03	0.36 ± 0.02	79.65 ± 4.02	6.02 ± 0.24

Applying fibre orientation effects on laminate properties

Young's modulus

The Young's modulus, also known as tensile modulus of the laminate is estimated by using the rule of mixtures for the thickness of the laminate since the density per laminae is estimated to be constant. The layup of the laminate including thicknesses is presented in table 5 where the Bi-axial material is assumed to be one layer of [±45°] resulting in two layers. The percentage contribution to the total thickness of the laminate is calculated per layer. The percentage of the total flexural modulus for the layers is determined in the previous paragraph and was imposed on the flexural modulus of the UD laminate generated using the synthesizer of Granta. The total flexural modulus of the laminate can now be calculated by multiplying the thickness contribution in percentages with the flexural modulus for each ply and adding them. This resulted in an estimated flexural modulus of 31 GPa .

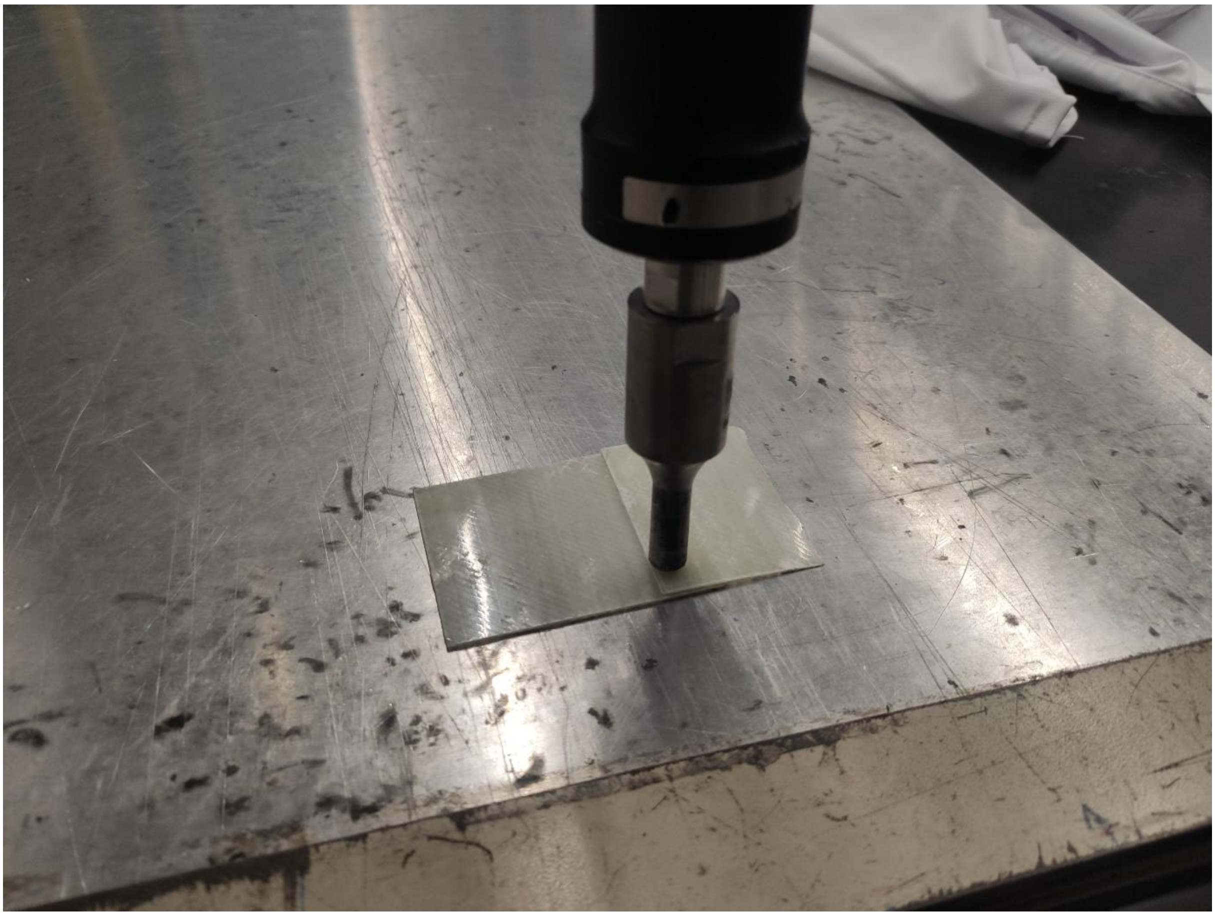
Tensile and compressive strength

A more conservative approach was used to estimate the tensile and compressive strength. Because failure of the ply stack will start with the weakest layer, after which the load is distributed over the remaining layers, I assumed that failure of one layer is equal to failure of the complete ply stack. This means that strength of the Bi-axial [±45°] is dictating. Imposing the knockdown factor from the fiber orientation resulted in a tensile strength of 108 MPa and a compressive modulus of 259 MPa. An interesting finding is that due to the fiber orientation, the compressive strength is higher than the tensile strength whereas in a 0° orientation this is vise-versa.

Table 5

				Strengths				Modulus	
Ply number	Fibre orientation	Thickness (mm)	percentage thickness	Residual Tensile strength	Tensile strength (Mpa)	Residual compressive strength	Compressive strength (Mpa)	Residual Young's modulus	Young's modulus (Gpa)
1	0	0.6	55%	100%	983	100%	809	100%	37
2	±45°	0.5	45%	11%	108	32%	259	63%	23
Result		1.1			**108**		**259**		**31**

Appendix H - Bonding experiment 1 – Ultrasonic



Context/Goals

The goal of this experiment was to evaluate the compatibility with the laminate, mostly the Elium matrix material, and the ultrasonic welding technique.

Layup

Unidirectional 600g/m^2 layer made out of several 75mm wide strokes followed by a layer of [-45/45] Bi-axial non crimp 812g/m^2. This laminate was made using the resin infusion process and yielded 1.1 mm thick plates.

Process

The process of ultrasonic welding of flat plates is rather easy. The machine was set up by someone with experience welding similar thickness carbon composite plates. The machine can be seen in figure 1 and comprises of a power supply unit and a hand held horn. The welding power 'weld' was set at 25 and the time (hold) at 20. The actual unit for both is not known. After set up the plates were overlapped, the horn pressed on the plates and after a click of the button, the plates were welded. Because of the vibrations the horn starts to wander so some tries were needed before I was able to hold it still. Some smoke was visible at the deeper welds.

Figure 1: Power supply

Figure 2: The horn on the plates

Results

The result is a surprisingly strong weld for a first try. Figure 3 shows two plates bonded with three spot welds. Figure 4 shows that the plates can be deformed without the welds breaking. Even though this looked promising, when bending in the perpendicular direction the welds broke rather easily. This could be due to suboptimal settings of the weld but also likely is that the welding actually creates some dry spots in the laminate. This is thought to be the case as examination of the broken weld a white patch can be seen signaling absence of matrix material.

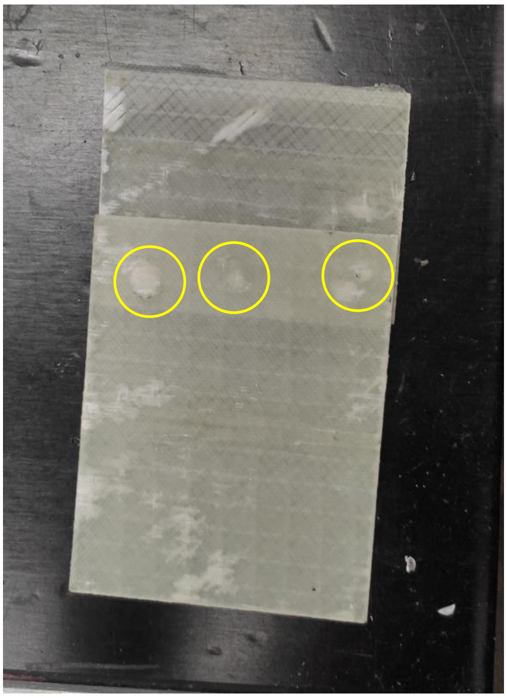


Figure 3: Three spot welded plates

Figure 4: Trying out the strength of the weld

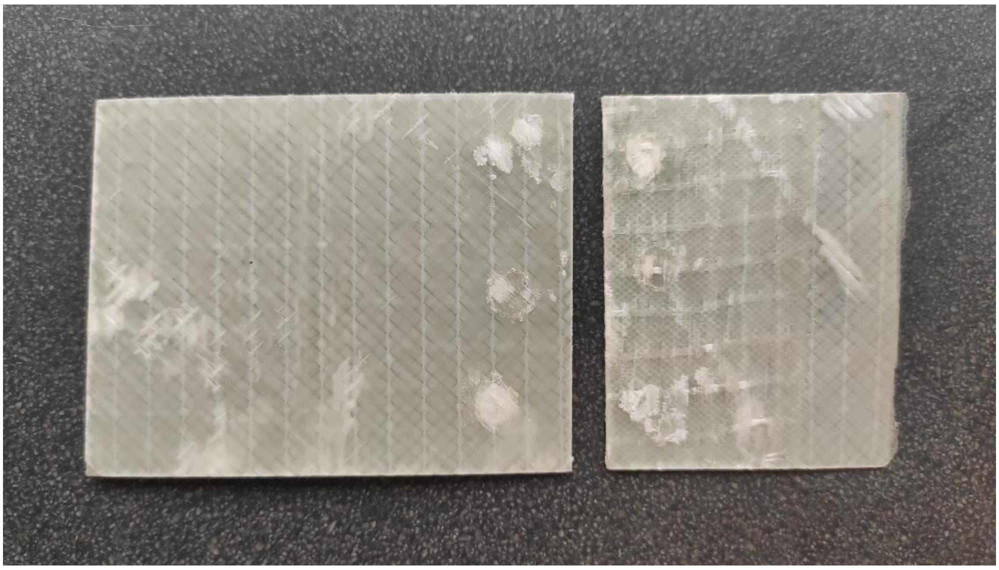


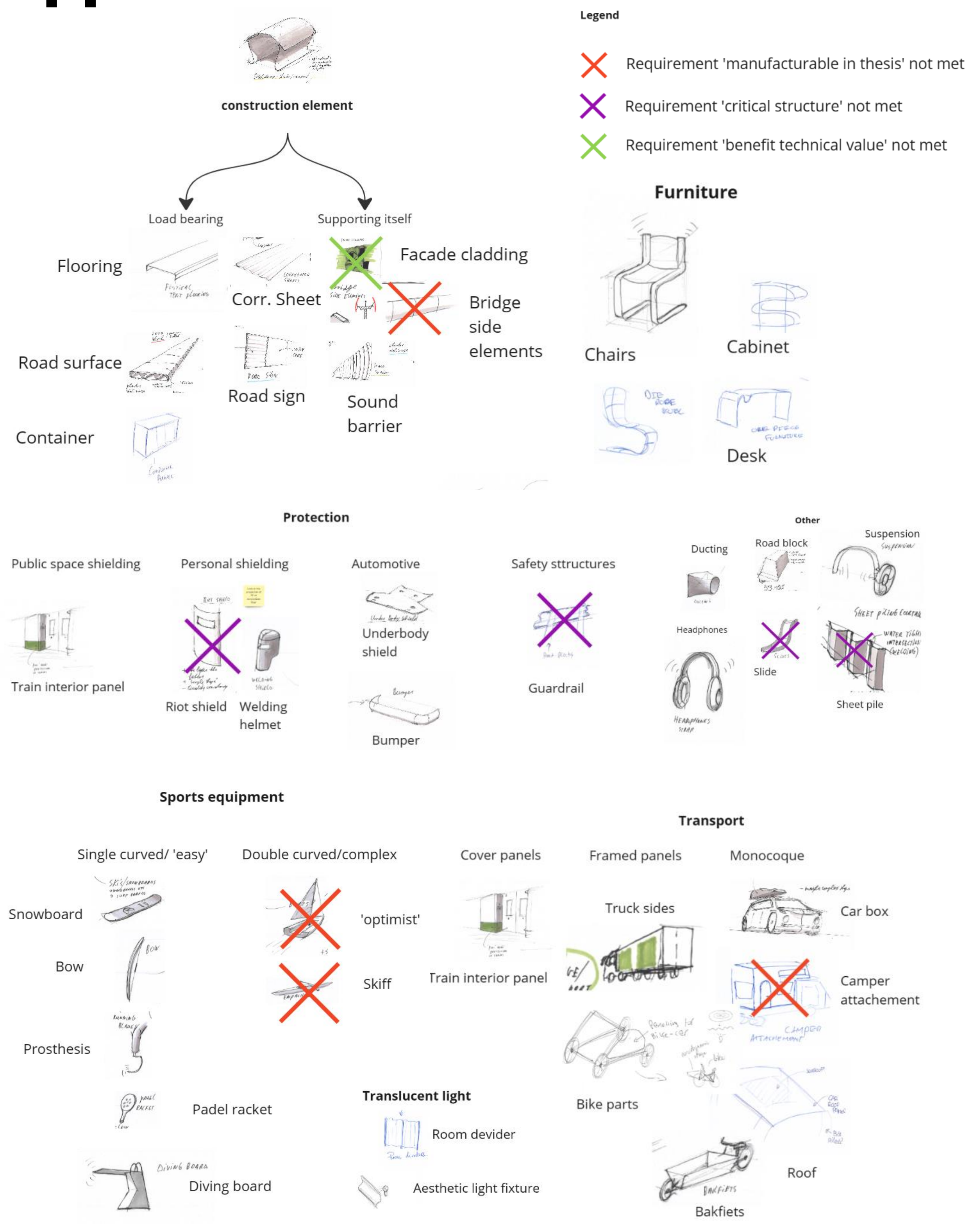
Figure 5: Broken weld and dry spots indicated by the white areas

Conclusion/Future work

The current welds were not strong enough to be actually used as bonding method. In the future some more testing should be performed to optimize the power and time setting of the machine. Alternatively other ways of bonding the material should be assessed. These include:

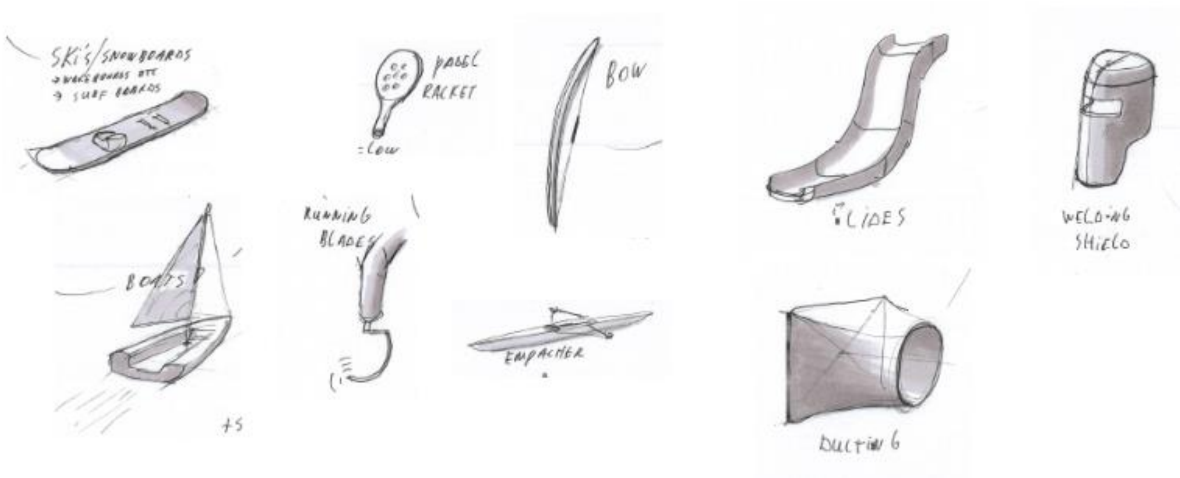
- Hot plate or hot gas welding
- Solvent welding
- Adhesive bonding, this might be possible with a thickened version of Elium. Cotton flocs for instance could be added to thicken the Elium similar to thickening epoxy.

Appendix I – Ideas



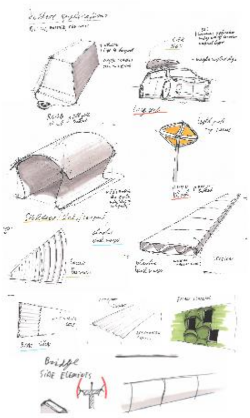
Appendix J – Ideas from 'Substitution' and 'optimized design requirements

From: Substitution

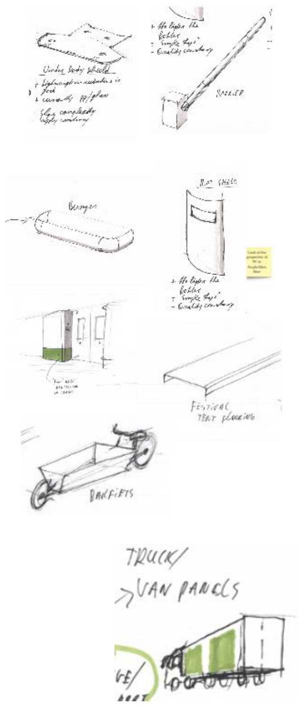


From: Optimized Design requirements

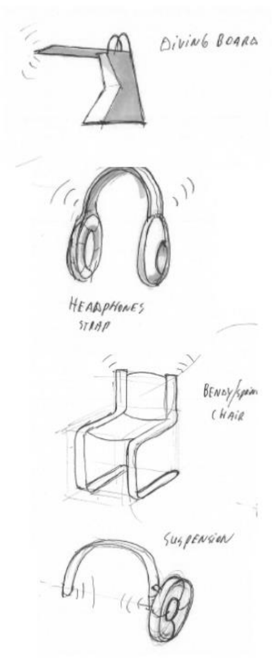
Outdoor applications



Lightweight & impact resistant



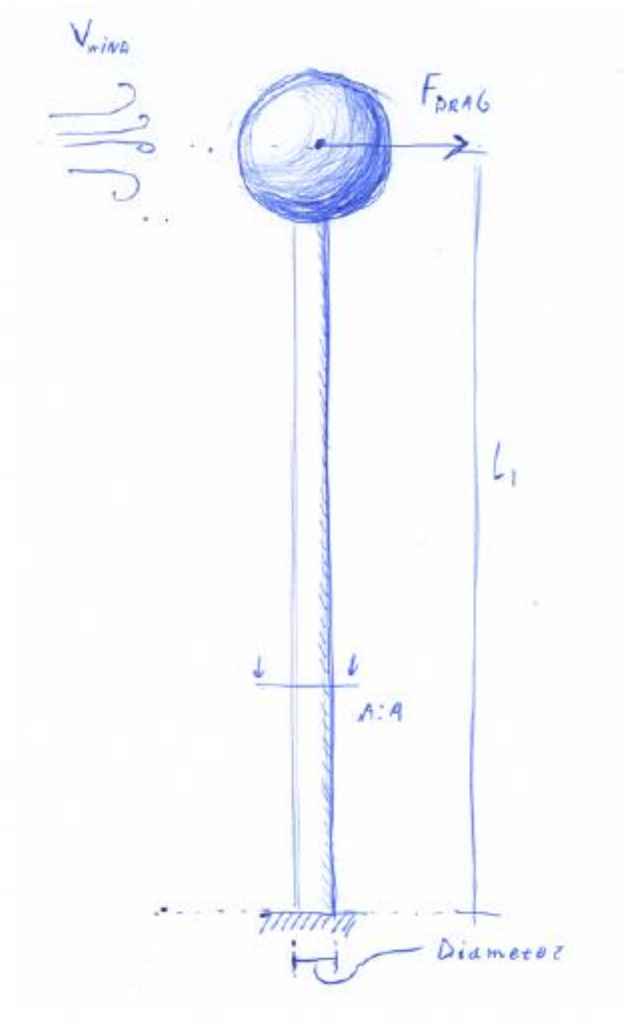
'Spring' operation



Appendix K: Strength and stiffness of lamppost

[> *restart;*

Loadcase



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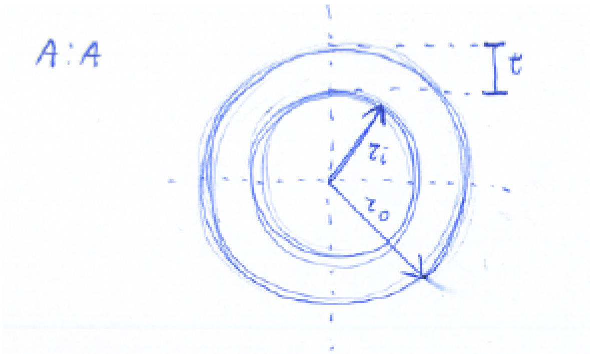
Variables and factors



Geometric conditions:

> $L1 := 3:$

> $diameter := 60:$

> $t := 2:$

> $R := \frac{diameter}{2} - 0.5 \cdot t;$

$$R := 29.0 \tag{2.1}$$

> $ro := evalf\left(\left(\frac{diameter}{2}\right) \cdot 10^{-3}\right);$

$$ro := 0.03000000000 \tag{2.2}$$

> $ri := evalf(ro - t \cdot 10^{-3});$

$$ri := 0.02800000000 \tag{2.3}$$

> $Ixx := evalf\left(\frac{1}{4} \cdot \mathrm{Pi} \cdot (ro^4 - ri^4)\right);$

$$Ixx := 1.534228188 \times 10^{-7} \tag{2.4}$$

Material property values:

Young's modulus [MPa]

> $Ey := 19.6 \cdot 10^3:$

longitudinal and transverse Flexural modulus [GPa]

> $Ef1 := 19.6:$

> $Ef2 := 19.6:$

in-plane shear modulus [GPa]

> $G := 10.5:$

Partial material factor determined from EN 40-3

> $\gamma m := 1.5:$

Plastic modulus of closed regular cross-section determined from EN 40-3

> $Zp := 4 \cdot R^2 \cdot t;$

$$Zp := 6728.00 \tag{2.5}$$

Characteristic yield strength [MPa]

> $fy := 268 :$

Other factors and constants:

Strain

> $\varepsilon := \left(\frac{R}{t}\right) \cdot \mathrm{sqrt}\left(\frac{fy}{Ey}\right);$

$$\varepsilon := 1.695537360 \tag{2.6}$$

When 1.53<ε<2 the following formula can be used for obtaining factor ϕ1 used in calculating the benınding moment of resistance.

> $\phi 1 := 0.81 - 0.3 \cdot (\varepsilon - 1.5)^{0.9};$

$$\phi 1 := 0.7409397689 \tag{2.7}$$

>

Poissons ratio longitudunal and transverse (assumed equal for QI layup)

> $v12 := 0.288 :$

> $v21 := 0.288 :$

>

Factor K to be multiplied with φ1 According to EN 40-7 for composite columns

> $K := \left(2 \cdot \left(1 + v12 \cdot \left(\frac{Ef2}{Ef1}\right)^{\frac{1}{2}}\right) \cdot \left(\frac{Ef2}{Ef1}\right)^{\frac{1}{2}} \cdot \left(\frac{G}{Ef1}\right)^{\frac{1}{2}}\right)^{\frac{1}{2}};$

$$K := 1.373112865 \tag{2.8}$$

Constant derived from EN 40-7 related to the material properties and the size of the door opening. Determining this facotr is determined out of scope of this Thesis and is thus set at 1.

> $\eta := 1 :$

Dead loads

> $MArmature := 9.6 :$

> $SafetyFactor := 1.5 :$

> $g := 9.81 :$

> $Fz := -MArmature \cdot g \cdot SafetyFactor;$

$$Fz := -141.2640 \tag{3.1}$$

Wind loads

Calculate drag of a sphere:

Drag coefficinet of a sphere

> $Cd := 0.45 :$

Wind speed

> $vwind := 35 :$

Frontal area not of the sphere but the armature measured in SolidWorks

> $Afront := 0.28 :$

International standard atmosphere (ISA): 101.325 kPa 20degC

> $\rho := 1.204 :$

Resulting drag force

> $Fdrag := 0.5 \cdot \rho \cdot Cd \cdot Afront \cdot vwind^2$

$$Fdrag := 92.91870000 \tag{4.1}$$

Bending moment

> $Mx := L1 \cdot Fdrag$

$$Mx := 278.7561000 \tag{6.1}$$

Bending moment of resistance NEN-EN 40-3-3

>

For closed regular sections

> $Mup := \frac{fy \cdot \phi 1 \cdot K \cdot Zp}{10^3 \cdot \gamma m};$

$$Mup := 1222.978042 \tag{7.1}$$

>

Acceptable strength NEN-EN 40-3-3

If equal or lower than 1 strength is acceptable

> $\frac{Mx}{Mup};$

$$0.2279322199 \tag{8.1}$$

Buckling NEN-EN 40-3-3

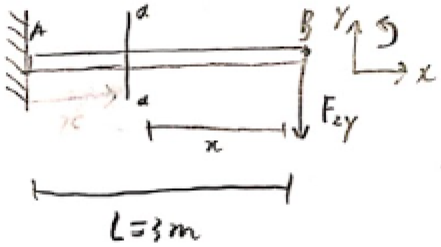
Buckling strength [Gpa]

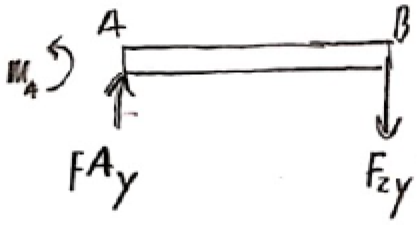
> $\sigma b := \left(\frac{Ef1 \cdot Ef2}{3 \cdot (1 - v12 \cdot v21)} \right)^{\frac{1}{2}} \cdot \left(\frac{t}{R} \right) \cdot \eta$

$$\sigma b := 0.8149472779 \tag{9.1}$$

>

Internal moment and shear forces





> $Fzy := evalf\left(Fz \cdot \cos\left(\frac{\text{Alpha} \cdot \text{Pi}}{180}\right)\right);$

$$Fzy := -141.2640 \cos(0.01745329252\ A) \tag{10.1}$$

> $Fzx := evalf\left(Fz \cdot \cos\left(\frac{(90 - \text{Alpha}) \cdot \text{Pi}}{180}\right)\right)$

$$Fzx := -141.2640 \cos(1.570796327 - 0.01745329252\ A) \tag{10.2}$$

> $sumFy := 0:$

> $sumFx := 0:$

> $sumM := 0:$

> $eq1 := sumFx = FAx + Fdrag:$

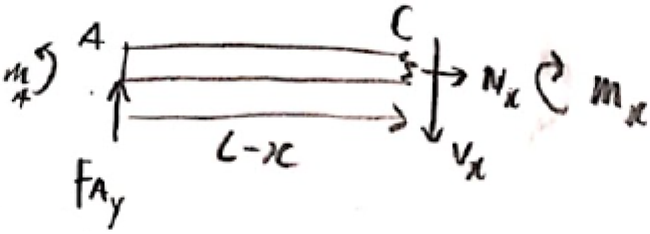
> $eq2 := sumM = Fdrag \cdot L1 + MA:$

> $FAx := evalf(solve(eq1, FAx));$

$$FAx := -92.91870000 \tag{10.3}$$

> $MA := evalf(solve(eq2, MA));$

$$MA := -278.7561000 \tag{10.4}$$



> $sumFx1 := 0:$

> $sumFy1 := 0:$

> $sumMA := 0:$

> $eq2 := sumFx1 = FAx + Vx1 :$

> $eq3 := sumMA = -Mx1 - Vx1 \cdot (L1 - x) :$

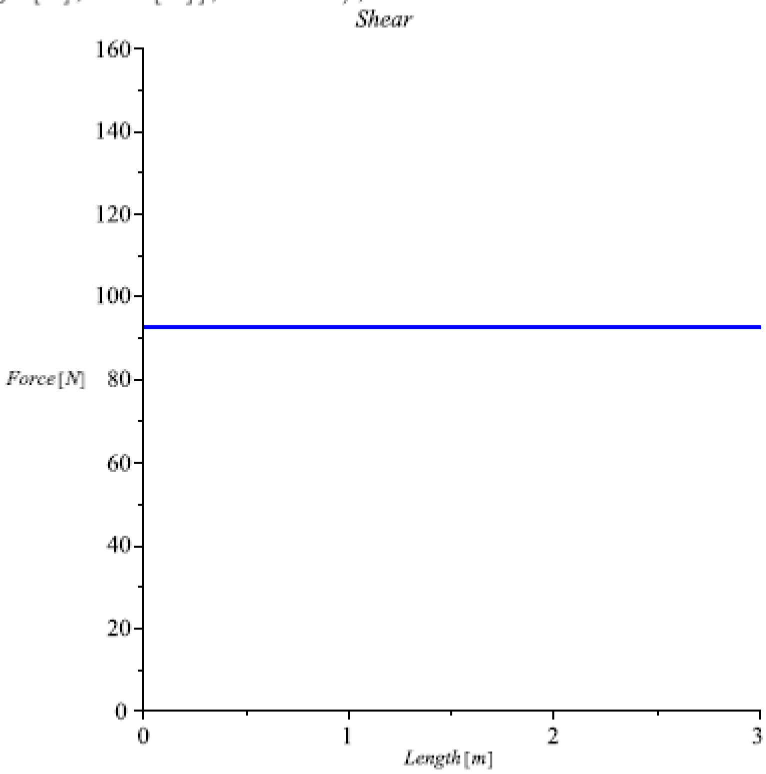
> $Vx1 := evalf(solve(eq2, Vx1));$

$$Vx1 := 92.91870000 \quad \textbf{(10.5)}$$

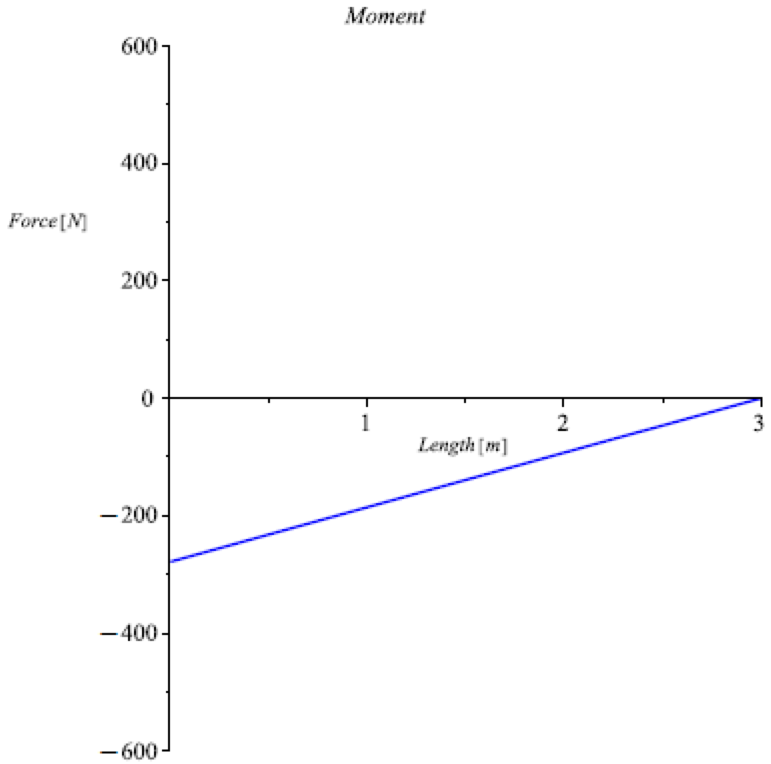
> $Mx := evalf(solve(eq3, Mx1));$

$$Mx := -278.7561000 + 92.91870000\, x \quad \textbf{(10.6)}$$

> $plot(Vx1(x), x = 0..L1, y = 0..160, color = blue, labels = [Length\ [m], Force\ [N]], title = Shear);$



> $plot(Mx(x), x = 0..L1, y = -600..600, color = blue, labels = [Length\ [m], Force\ [N]], title = Moment);$



Internal stress

> $A := \mathrm{Pi} \cdot ro^2 - \mathrm{Pi} \cdot ri^2;$

$$A := 0.0003644247479 \qquad \textbf{(10.1.1)}$$

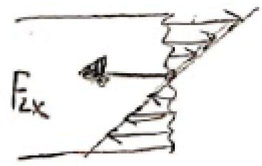
> $y := ro;$

$$y := 0.03000000000 \qquad \textbf{(10.1.2)}$$

> $Mmax := -Vx1;$

$$Mmax := -92.91870000 \qquad \textbf{(10.1.3)}$$

The force component along the length of the pole Fzx should be substracted from the maximum tensile stress and added to the maximum compressive strength



> $\sigma TensileMax := \frac{Mmax \cdot y}{Ixx} - Fz;$

$$\sigma TensileMax := -1.816900087 \times 10^7 \quad \textbf{(10.1.4)}$$

> $\sigma CompressMax := \frac{Mmax \cdot y}{Ixx} + Fz;$

$$\sigma CompressMax := -1.816928339 \times 10^7 \quad \textbf{(10.1.5)}$$

> $Tensilestrength := 979E6$

$$Tensilestrength := 9.79 \times 10^8 \quad \textbf{(10.1.6)}$$

Deflection

> $vda := \frac{Mx}{Ey \cdot 10^6 \cdot Ixx};$

$$vda := -0.09269970471 + 0.03089990157\, x \quad \textbf{(10.2.1)}$$

> $va := int(vda, x) + C1;$

$$va := -0.09269970471\, x + 0.01544995078\, x^2 + C1 \quad \textbf{(10.2.2)}$$

> $v := int(va, x) + C2;$

$$v := -0.04634985236\, x^2 + 0.005149983593\, x^3 + C1\, x + C2 \quad \textbf{(10.2.3)}$$

> $x := 0 :$

> $eq1 := va = 0;$

$$eq1 := C1 = 0 \quad \textbf{(10.2.4)}$$

> $eq2 := v = 0;$

$$eq2 := C2 = 0 \quad \textbf{(10.2.5)}$$

> $C1 := rhs(eq1);$

$$C1 := 0 \quad \textbf{(10.2.6)}$$

> $C2 := rhs(eq2)$

$$C2 := 0 \quad \textbf{(10.2.7)}$$

> $x := L1 :$

> $MaxDeflection := v$

$$MaxDeflection := -0.2780991142 \quad \textbf{(10.2.8)}$$

> $AllowedDeflection := 0.04 \cdot L1;$

$$AllowedDeflection := 0.12 \quad \textbf{(10.2.9)}$$

>

Appendix L: Calculation absorption of blade waste

This appendix shows how the amount of absorbed material is calculated.

Assumptions

- All panel classes can be used in this application
- Spar caps cannot be used in application
- The yearly 400 decommissioned blades are of reference blade size (75m).
  - Amount of blades will however increase in the future
  - 75m is offshore size but a lot of the 400 blades will be from onshore source which are smaller blades.
  - Assumed is that the possibly unrealistic low amount of decommissioned blades will be countered by the unrealistic assumption that all decommissioned blades are 75m.
- Ribs itself are not taken into account -> too little information about their design geometry
- No cutting losses are taken into account

How to calculate

It was chosen to calculate percentages based on surface area. This is because no information was found for the reference blade about material thicknesses outside of the 30-45m section of the blade. This made calculations based on weight impractical.

Percentage in scope surface area material

When calculated based on outer surface area, about 24% of the material is out scope. This figure is based on the following calculation:

- Total surface area of the blade's outer surface=580m^2
- In scope surface area = 440m^2
- Percentage in scope surface area = 440/580x100=76%

Percentage usable surface area within scope

For the lamppost application, the spar caps cannot be used but are a big part of the blade in surface area and even more in weight or volume. The bond lines cannot be used in general. The result is that 68% of the in-scope surface area can be used to make lamp posts. This is based on the following calculation:

- Sparcaps surface area = 148m^2
- Bond line surface area = 16m^2
- Useable area = 520-148-16 = 356m^2
- Percentage in-scope useable surface area = 356/520x100=68%

Percentage Dutch lamp posts that can be made from decommissioned TPC WTBs

Surface area used by application

In total about $2m^s$ of material is used by the application. This is a rounded-up number because the amount used in the hatch reinforcement and production losses are not known. The bottom section, top section and luminaire cover respectively use $0.7m^2$, $0.5m^2$ and $0.4m^2$ for a total of $1.6m^2$.

Amount of lamppost from one blade

In total about 356 lamppost can be made from one turbine blade. As the application uses face plies split from the core the actual usable surface are should be doubled resulting in $712m^2$. Since the application takes up about $2m^2$, in total about 356 lamp posts can be made from one 75m TPC blade.

Absorption of yearly supply of lamppost

The Netherlands counts between 3 and 4 million lamppost ("Hoeveel lantaarnpalen zijn er in Nederland?," 2016). About 1/30th of these posts are annually replaced ("'Openbare verlichting is nog niet slim en energiezuinig genoeg' | Change Inc.," n.d.). When assuming the Netherlands counts 3.5 million lampposts, about 117.000 lamppost are replaced annually (3.5E6/30).

According to J. de Krieger from Blade-Made currently about 400 blades are disposed every year (Krieger, 2023). When assumed that from every blade an equal amount of lampposts can be made this, results in a total of 142.400 lampposts(400x356).

117.000 lampposts are needed but 142.400 are needed. This is a surplus of about 20%. However this is a calculation based on a 3m tall posts while in reality most lampposts are between 4 and 8m tall. An assumption can therefore be made that the demand of lamppost can be fully saturated by the usable and in-scope material from the WTBs.

Amount of used material

No exact figures were found describing weight contribution of elements like the panels and spar caps to the total weight of the reference TPC WTB blade. To make a claim about the amount of used material in weight, figures from another blade (NREL 5MW) were used. In a paper describing segmentation of this blade is was found that the mid-span of the blade amounts to 58% of the complete blade mass. Zooming in on the mid-span, 63% of the weight is in panels, 33% in the spar caps and 3 wt% in the bond lines (Joustra, Flipsen, & Balkenende, 2021). The expected reference blade mass is 30 ton. This results in an inboard section weight of 17.4 ton (0.58*30) and . Within the scope, for this particular re-use application 11 ton of sandwich panels can be used (0.63*17.4).

Amount of core material waste

Because the face plies have to be split from the core, the core can be regarded as waste material. As the amount of core material throughout the entire mid span is not known, no exact figure of core material waste can be calculated. However an estimation can be calculated based on the 30-45m section where on average 76% of the thickness is foam. The density of foam used in the reference blade is $100kg/m^3$ compared to the laminates $1800kg/m^3$. When the thickness contribution of foam is assumed to be representable for all panels in the mid-span, the average density is $508\ kg/m^3$. This results in a total panel volume of $21.7m^3$ (11000/508) which when the 76% thickness share by the foam is taken into account, results in $16.5\ m^3$ (0.76*21.7) foam used in the mid-span of the blade which is 1650kg (16.5*100). It can be concluded that from the mid span panels about 15% in weight is waste from core material (1650/11000*100). For the total midspan, Including spar caps, this is about 9.5 wt% (1650/17400*100).

Midspan usable material

Combined with the 3 wt% loss in the bond lines, in total 12.5 wt% (9.5+3) of the midspan can be considered waste (bond lines + core material). 33 wt% from the spar caps is not considered waste but cannot be used in the lamp posts. In total 45.5% (33+12.5) of material from the mid span cannot be used for the lampposts. This relates to 54.5 wt% of unusable material in the mid span (100-45.5). This is 9483 kg (0.545*17400).

Amount of used material in total blade

Since the midspan is only 58 wt% of the entire blade, in total 32% can be used to make lampposts which is almost a third of the total blade mass (0.545*0.58).

Sources

de Krieger, J. Personal communication. Retrieved April 3, 2023

Hoeveel lantaarnpalen zijn er in Nederland? (2016). Retrieved January 24, 2023, from https://www.recyclingmagazine.nl/algemeen/hoeveel-lantaarnpalen-er-nederland/28936/

Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural reuse of wind turbine blades through segmentation. *Composites Part C: Open Access*, *5*(March), 100137. https://doi.org/10.1016/j.jcomc.2021.100137

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Appendix M: Short interview

The purpose of this interview is to find out whether (part of) the design vision is achieved with this demonstrator. This vision is not disclosed because it can be directive.

What is your profession? For students: specialization/qualifications	
Are you familiar with wind turbine blades?	
Are you familiar with composite materials??	

I will now briefly present the context before moving on to my questions.

Do you have any questions about the context or the material?	
Now that you have seen the context and the demonstrator, what would you like to design with WTB material yourself?	
Did this demonstrator help you in your thought process to come up with other applications?	
If so, why?	

Thank you for your time and insights. If you are interested in the final result, you can leave your contact details here:

Name:

Phone/Email:

Thank you very much.