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From blade to post
reshaping thermoplastic wind turbine blade

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FROM BLADE TO POST: RESHAPING THERMOPLASTIC WIND TURBINE BLADE MATERIAL

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ABSTRACT

Wind turbine blades, though key to green energy, pose recycling challenges due to their material composition. This study explored reshaping thermoplastic composite blades—an emerging, more recyclable design—into useful applications without altering the material composition. First, key characteristics like material structure and thickness were defined after which sample material was produced. Reshaping experiments were conducted for both single and double curved geometries with different reshaping methods and parameters. The promising results were translated into a demonstrator re-use application, a lamppost, showcasing reshaping as an alternative to shredding in circular blade strategies.

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1. INTRODUCTION

Wind energy is an increasingly valuable resource in the search for green energy. Currently most turbines are expected to last for 20 to 25 years with ongoing research to prolong this lifetime [1]. While most components of the wind turbine can be recycled well, the wind turbine blades (WTBs) cannot [2]. Combined with the increasing production of blades, a waste stream of hard to recycle material will sprout at an alarming 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 [3]. These numbers are concerning when problems in the disposal of WTBs are not solved.

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 thermoset counterparts [4,5] Research showed that chemical separation of fibers is possible with low energy usage [4]. Other research initiatives like the ZEBRA consortium focus on the retrieval of both the fibers and the matrix [6]. Even though these material recovery options look promising, they are focused on recycling, breaking up the material composition and lowering its value.

Joustra et al. described in their research that reverse forming of glass fibre reinforced polypropylene is possible without significant stiffness or strength loss, retaining the value of the material [7]. This leaves the question if material originating from TPC WTBs can also be re-used by thermoforming sheets into re-use applications.

This study forms an explorative base for further, more detailed research into the shaping limits and re-use potential of TPC WTBs waste.

3. RESEARCH TESTS & EXPERIMENTS

3.1 Defining the material

Before reshaping experiments can be conducted, the material should be defined as the structure of the fibre reinforcement as well as the matrix material can have a big influence on the reshaping performance. A reference blade in combination with a segmentation pattern is used to define the shape, curvature, fibre orientation and thicknesses of retrieved material.

3.1.1 Reference blade geometry and materials

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 publicly available of a TPC WTB [5]. Whereas most geometric design aspects of this reference blade are similar to existing blades, some relevant differences were found. Due to processing opportunities resulting from the use of a thermoplastic material 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 [5]. 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. From the geometric data described in Joncas’s thesis a CAD model was constructed.

The theoretical reference blade is constructed from glass fibre reinforced anionic PA-6 which is an infuseable thermoplastic matrix material. Similar to current blade designs, Joncas described two different layers of fiber orientation for the shells and shear webs: 0° and ±45°. Fibre direction of the spars is recorded to be predominantly 0° in spanwise direction. The types of fabrics as well as the core material are however not presented and were defined with the help of literature and expert opinion from J. Teuwen [8] and S. Jansma [9].

3.1.2 segmentation

A segmentation pattern aims to retrieve pieces of material without extreme variations in geometry or material use while also avoiding areas prone to damage. Following Joustra et al. [10] a division is made between the inboard, midspan and outboard sections of the reference blade. In this research only the midspan of the blade is considered for material retrieval. The boundaries of the segmentation are based on the following:

- Challenging or non-reshapable parts of the blade such as bond lines. Ridges of adhesive in the bond lines of the blade 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 and size of the bond line can vary.

- Leading edge damage which is common in WTBs [11]. 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 [12].

3.1.3 Panel classification

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. 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 shells and 'leading' and 'trailing' for the shear webs. 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. The radius was determined using the following equation: $r = L^2/8h + h/2$. 'L' is the chordwise length of the panel and 'h' being the height difference of the panel perpendicular to the chord line L.

3.2 Reshaping experiments

Joustra et al. [7] showed that flattening a curved thermoplastic composite part is possible without significant strength or stiffness loss. The wind turbine blades however use a different fibre structure and matrix material and the initial material is quasi flat instead of curved. Most parts of the blade skins are made of sandwich structures with either a foam or balsa wood core. It was decided to only look at reshaping of the face plies as this will greatly increase the shapeability. Sandwich panels are weak in peel which makes it likely that face sheets can be retrieved without a core. Since this is a new field of research, it was decided to experiment with different shapes and visually identify defects rather than fully researching one specific geometry including mechanical testing. The outcomes of this research are therefore not definitive and should spark interest in further research

3.2.1 Simulated WTB sheet

At the time of conducting this research, a single large scale thermoplastic composite wind turbine blade existed, namely the blade made in the Zebra consortium. Unfortunately it was not possible to perform reshaping experiments on a real wind turbine blade piece. Members of the consortium however provided knowledge and materials of which a single monolithic sheet was manufactured that resembles a face sheet of a real blade.

Even though fiber material and orientation remained similar, other material design aspects from the simulated sheets differ from the reference blade. The matrix material was switched from anionic PA-6 to a type of PMMA with the brand name Elium, manufactured and supplied by Arkema. Elium 188XO was selected. For the 45° fibers, 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 which is representative of what is used in real blades. Instead of 1000g/m2, Polyservice UD tape 600 g/m² was used for the spanwise UD fiber layer. 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 inter-ply slippage [13]. Both are dependent on the type and weight of the fabric in the layup. Inter-ply slip is dependent on the amount of ply-ply interfaces, whereas intra-ply shearing is dependent on the weaving or stitching pattern of the fabric. Switching from 1000g/m2 fabric to 600g/m2 tape thus likely influences results in reshaping efforts.

The glass fiber was infused with the matrix using the vacuum assisted resin infusion method with a real blade section as a mould to resemble similar curvatures.

3.2.1 Setup

For all reshaping experiments, thermoforming was used where the laminate is heated to temperatures well above Tg ranging between 140-190°C after which pressure is applied to make the laminate conform to the chosen mould shape. Care was taken to not apply significant pressure before the forming temperature was reached to avoid damage to the laminates. The laminate temperature was measured by use of thermocouples and the distribution of temperature was measured with an infrared camera (Voltcraft WB-80). 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 buildup of internal stresses. Apart from this general method a distinction can be made on process parameters such as how the reshaping pressure is applied, temperature and mould shape. The set of process parameters for each experiment can be seen in Table 1. Experiments 1 and 2 use a double layer of the bi-axial material in +-45° direction to the mould length axis while experiment 3 and 4 consisted of both bi-axial and UD fabric as intended. The UD layer was oriented in mould direction facing in experiment 4 and facing away the mould surface in experiment 3.

Table 1: Overview of the reshaping experiments

		Laminate		Process parameters					
#	**Title**	**Layup**	**Thickness (mm)**	**Method**	**Applying heat**	**Reshaping temp (°C)**	**Reshaping pressure (mBar)**	**Mould shape**	**Radii (mm)**
1	Vacuum bag forming	2× 812g/m² bi-axial [+45°] of length axis mould	1.2	Vacuum bag forming	Convection	180–190	54–75	Conical	40 / 24
2	Corrugated sheet	2× 812g/m² bi-axial [+45°] of length axis mould	1.2	Vacuum bag forming	Convection	165–180	Step 1: 600, Step 2: 6	Wave	±20 / ±20
3	Dome shape	812g/m² bi-axial [+45°] + 600g/m² UD of length axis mould	1.1	Vacuum bag forming	Convection	165–180	85–120	Dome	125 / 125
4	Tube rolling	812g/m² bi-axial [+45°] + 600g/m² UD of length axis mould	1.1	Laminate rolling	Convection/ conduction	140–160	Unknown	Tube	30 / 30

Initially a similar setup found in reverse forming research from Joustra et al. [7] was used with a semi circular mould and a vacuum bag to draw the laminate over the mould surface at 190°C. The setup after shaping can be seen in figure 1 while figure 2 shows the

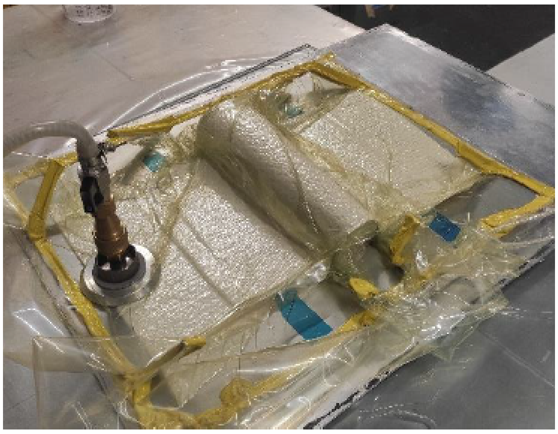


Figure 1: Reshaping experiment 1, formed

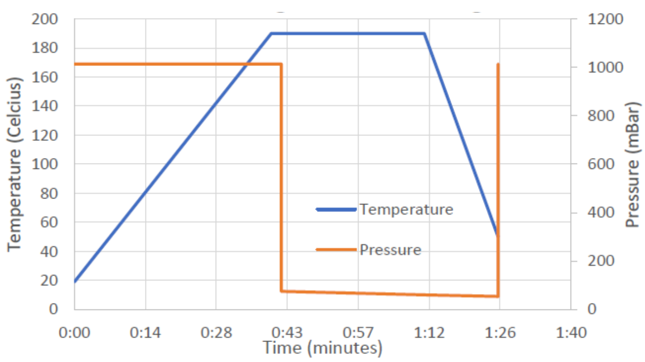
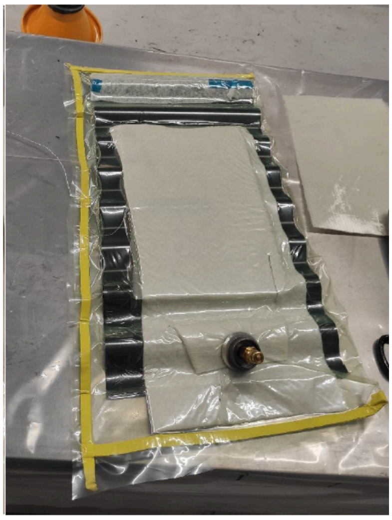


Figure 2: Pressure and temperature development (1)

temperature and pressure development over time.
The geometry was then changed to a corrugated sheet as this could be an interesting re-use application (Figure 3). The shaping temperature was decreased to 180°C and a similar pressure profile was used as seen in figure 4.



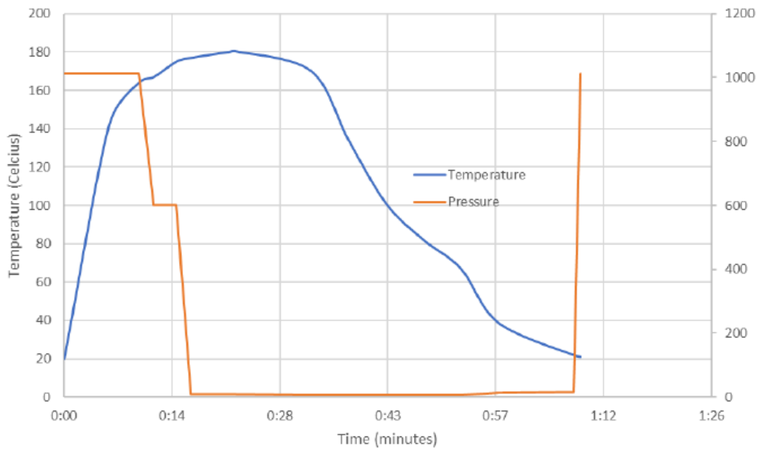
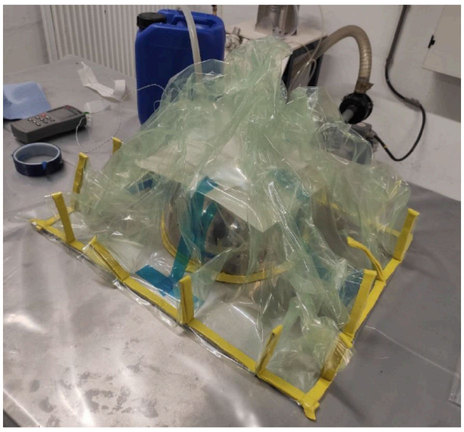


Figure 3: Reshaping experiment 2

Figure 4: Pressure and temperature development (2)

To assess double curved reshaping performance, a dome was used as a mould, again using a vacuum bag for the application of reshaping pressure.



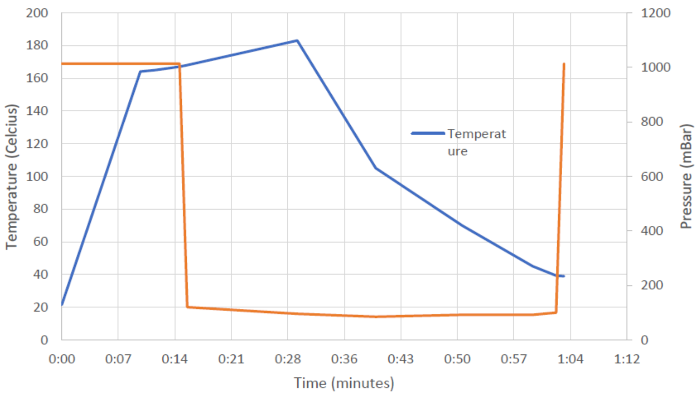


Figure 5: Reshaping experiment 3

Figure 6: Pressure and temperature development (3)

Finally a different reshaping method was used to form a tube, extending the findings from the semi circular mould. This method differs from the other experiment in that the forming pressure is applied by rolling the laminate on a tube while keeping the laminate under tension rather than vacuum pressure. The laminate is attached to an aluminum tube with heat resistant tape on one side while the other side is clamped to a table. The laminate was then heated with two heatguns fixed to an adjustable mount while at the same time the aluminium tube is heated from the inside with another heat gun. This ensures that the matrix remains shapeable when the laminate touches the mould. The setup can be found in figure 7. When the laminate was equally heated it was rolled on the mould while tensioning the laminate by pushing the tube horizontally away from the clamps. The infrared camera ensured that the laminate could be heated evenly by moving the heatguns accordingly. The development of temperature and pressure was not recorded.

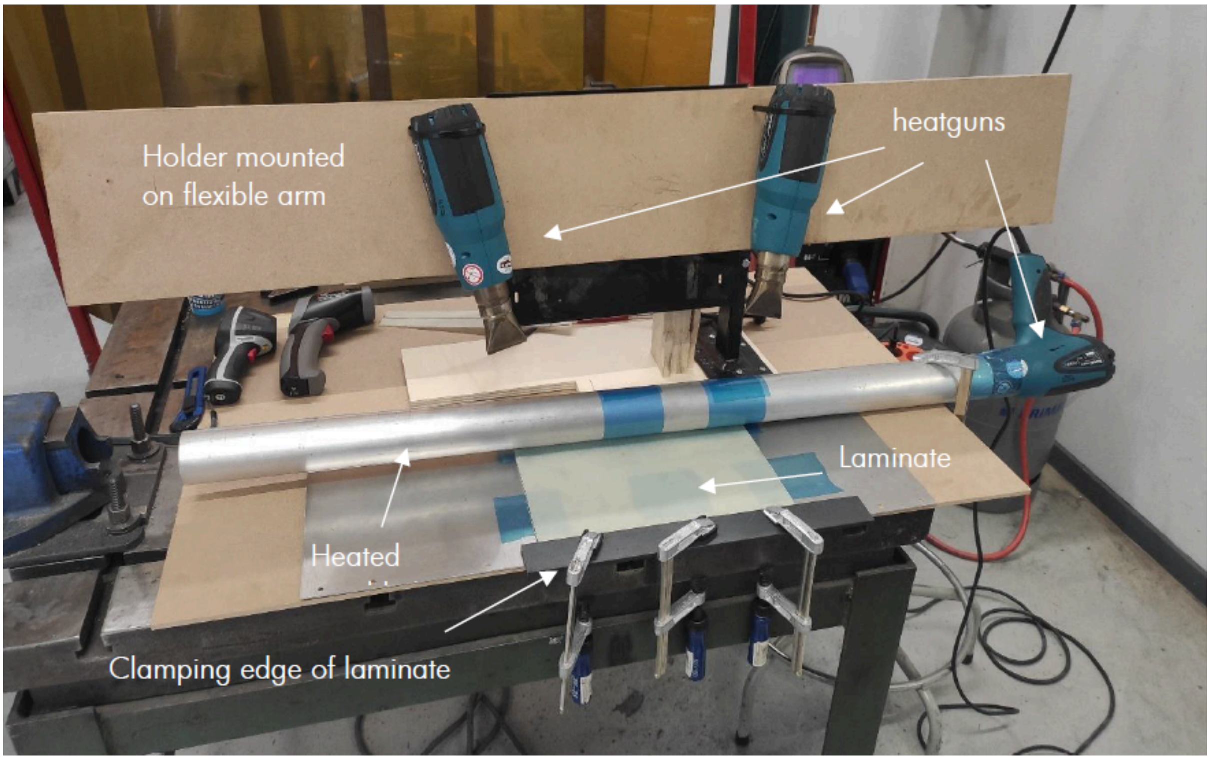


Figure 7: Setup of reshaping experiment 4

3.1 Demonstrator

It was decided to convert the findings found during the reshaping tests in a demonstrator product to use as a practical example of this novel circular end of life strategy. Manufacturing of an actual product also helps to inspire more research on this topic. Lastly more insights in the reshaping performance of the material are gained.

3.2.1 Design approach

The demonstrator should not only showcase the reshaping potential of the TPC WTB material but also make use of its technical value, have sufficient volume to repurpose large amounts of blade waste and finally inspire researchers and designers to use the structural re-use through re-shaping approach. With the help of creative sessions a large number of ideas were generated. A list of requirements followed by selection criteria was then used to reduce the number of suitable applications until one idea remained. This idea was then detailed with use of more specified requirements and expert opinion. Simplifications in geometry were added to be able to make the demonstrator without significant mold costs.

3.2.2 Material properties

After the product idea was detailed the structural feasibility of the design was evaluated using static equations found in EN-40. These equations aim at calculating maximum internal tensile stress, deflection and buckling at certain prescribed loads. Since the mechanical properties of the material were not measured in the research due to time constraints, an estimation was made.

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 glass fibre reinforced epoxy composites [14]. It was therefore decided to use typical strength and stiffness values of glass fibre, epoxy laminates with a quasi isotropic layup found in Granta's synthesizer tool [15].

3.2.3 Demonstrator manufacturing

Manufacturing of the demonstrator can be regarded as an extension on the reshaping experiments. Both reshaping experiments 3 and 4 used similar, though enlarged, setups and process parameters. However, no pressure or temperature measurements were recorded. Tubular mould radius increased from 30 to 35mm while the dome shape radius increased from 125 to 1000mm.

4. Results

4.1 Retrieved blade material

Projecting the segmentation boundaries onto the reference blade yields 168 panel sections which are presented per panel class in table 2.

The panel outline is trapezoidal. 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. Curvature classes are based on the curvature radius of 'medium' (0-2m), 'light' (3-5m), 'minute' (6-10m) and 'quasi flat' (>11m) and are presented per panel class in table 2. This table can be used when designing reuse applications. Because only data from the 30-45m section of the reference blade could be found, panel classification from the full range between the inboard and outboard sections cannot be given.

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. Although spar caps are not a panel like structure they were incorporated into Table 2 since valuable material could potentially be retrieved. Unlike the retrieved shell parts these beam-like structures run the entire length of the blade and almost all fibers lay in the spanwise direction making the panel's material properties highly anisotropic which can be exploited in re-use applications.

Table 2: Combined results from classification of panels, their size, curvature class, fibre orientation and thicknesses

Class	Subclass	Width (m)	Arc length/depth (m)		Curvature class		Fibre Orientation	Thicness (mm)		
			Inboard	Outboard	Inboard	Outboard	(0°=spanwise)	Total	Core	Face ply
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	9.3	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

4.2 Reshaping experiments

4.2.1 Simulated WTB sheets

The resulting laminates using the specified fabrics are between 1.1 and 1.2mm thick. 43% of the fibers are in spanwise direction with the rest of fibers in +-45° offset from the spanwise direction. This is similar tot the fibre orientations reported by Joncas [5] in the reference blade. By using Table 2 presented in chapter 4.1 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 plate thickness and are thus most likely.

4.2.2 Reshaping experiments

Table 3 shows an overview of the results of reshaping per experiment while figure 8 shows the results visually.

Table 3: Results of the shaping experiments

#	Title	Browning	Shape conformity	Fibre/matrix defects
1	Vacuum bag forming	Yes	Decent (bridging concave parts)	Fibre buckling, kink bands, fibre waviness, dry fibers
2	Corrugated sheet	Yes	Good (minor bridging concave parts)	Dry fibers
3	Dome shape	Yes	Bad	Heavy wrinkling, fibre buckling, kink bands
4	Tube rolling	Minor	Good (almost circular cross section)	Dry spots

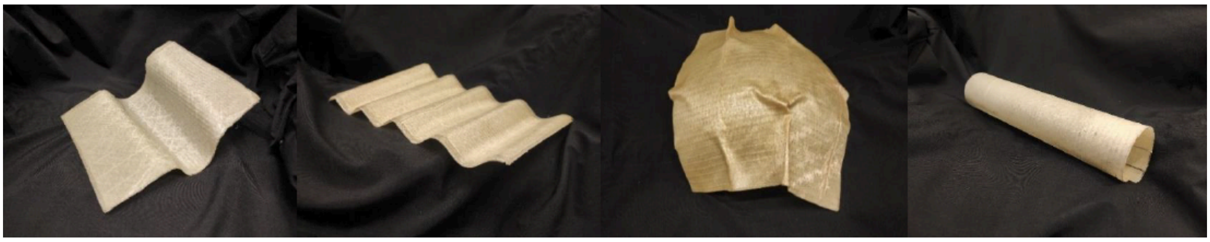


Figure 8: Results of the shaping experiments. From left to right: shaping experiment 1, 2, 3 and 4.

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 as can be seen in figure 9. Fibre waviness was identified on supported areas where the laminate is pressed between mould and vacuum bag (figure 10). Both fibre buckling and waviness could be a sign of insufficient inter-ply slippage which introduces internal compressive forces. By varying the reshaping temperature and speed these defects could be avoided as they play a vital role in inter-ply slip behaviour [7].

Figure 9: Fibre buckling on experiment 1

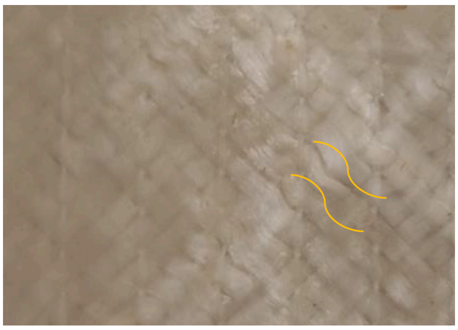


Figure 10: Fibre waviness on experiment 1

No fibre buckling or waviness was identified in experiment 4 'tube rolling' even though the radius and reshaping temperature is similar to that of earlier experiments. A likely explanation is the addition of an in-plane tensile force while rolling the laminate which counteracts in-plane compression loads of the laminate during reshaping and forces inter-ply slipping [7]. The heated tubular mould is believed to have no influence on the waviness as the moulds of other experiments were also heated.

Apart from the double curved experiment, vacuum bag formed parts conform well to the mould shape except for concave areas where bridging is found. This could be a result of inadequate tool-ply slip because the vacuum bag pins down the laminate on the convex parts of the mould [13]. The use of matched die forming could increase tool-ply slip and restrict fibre movement. However due to internal compressive force resulting from friction between plies, waviness will likely still occur in the laminate. Similar to the tube rolling, an in-plane tensile load could prevent this waviness.

The laminate reshaped into a double curved surface in experiment 3 did not conform to the mold shape showing heavy wrinkling and fibre buckling. This is likely a combination between processing and fibre structure. The vacuum bag forming method used in the experiments poorly prevents fibres from moving both in and out of plane. Stitching patterns of the non crimp fabrics prevent both intra-ply shear and inter-ply slippage which result in wrinkling of double curved surfaces. When using non stitched fabrics, intra-ply shear is facilitated resulting in better quality shapes [16].

The tube shape showed a large amount of white speckles as can be seen in figure 11. According to J. Teuwen the formation of white speckles found on several specimens is likely due to a fibre to matrix interface incompatibility as a result of non optimal fibre sizing [8]. The effect of the white speckles is exaggerated as melted matrix draws away from the fibres while at the same time contrast increases due to matrix browning. This browning occurred when temperatures reached above 160°C for longer exposure times. At the same time minimal browning occurred below 160°C or short exposure times with temperatures above 160°C. The light brown colour could be a sign of matrix degradation, however the resin manufacturer did not raise concerns as they see many virgin laminates with a similar colour resulting from the curing process at elevated temperatures [17]. The twist found in reshaped specimens is caused by the unbalanced and asymmetrical nature of the laminates.

Figure 11: Comparison of a 'virgin' laminate (left) and heated laminate (right) both showing white speckles at the cross section of fibre bundles

4.3 Demonstrator

4.3.1 Lamp post design

Following the material driven design approach lamppost were identified as a valuable re-use application. The lamppost makes use of the technical value of the material, is well integrated in society and is of industrial scale, ensuring a significant amount of material can be reused. Furthermore reshaping experiment 4 showed that tubular structures can be reshaped with relative ease. The luminaire cover provides a second double curved reshaping experiment with a large radius of 1000mm instead of the 250mm radius of experiment 3

As defined in 4.2.1 about half of the fibers of the retrieved material are UD in spanwise direction. This was chosen to be the direction for the length of the post to maximize bending stiffness. The remaining bi-axial layer then conveniently takes up torsional and other loads.

Results of calculating maximum deflection, buckling and tensile stress according to EN-40 showed that it is plausible to make a lamppost out of TPC WTBmaterial.

4.3.2 Lamp post manufacturing

In the proposed lamppost design the shaft is conical for aesthetic reasons. In the demonstrator this was replaced by straight sections to simplify the moulds.

After reshaping the tubular post section a visual inspection resulted in the following laminate defects:

- White speckles similar to figure 11.
- Laminate twist in the post sections resulting in a helicoidal seam.

Manufacturing of the double curved luminaire cover resulted in large wrinkles and fibre buckling. It was decided to showcase lamppost with the original luminaire cover.

Figure 12 shows the lamppost demonstrator.

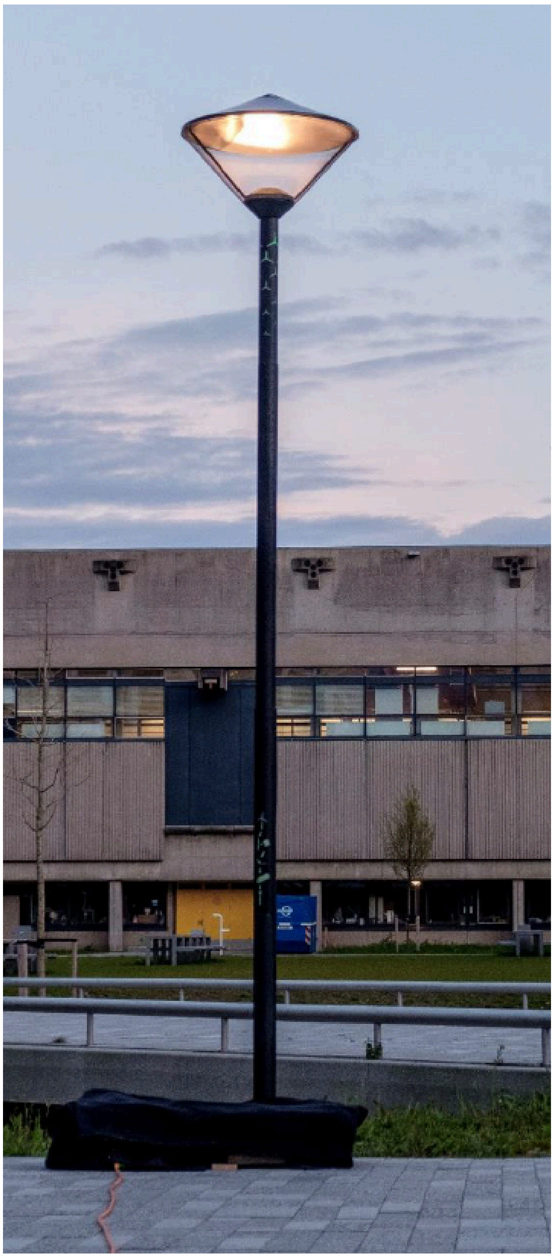


Figure 12: Lamppost demonstrator

5. Conclusions

5.1 Retrieved material

Thermoplastic composite wind turbine blades can have drastically different structures asking for novel segmentation methods. The reference blade analysis and segmentation showed that significant amounts of reshapable and technical high value materials can be liberated.

5.2 Reshaping performance and fibre structure

Reshaping experiments showed that single curve reshaping is relatively easy when thin face plies are separated from the core material. Small radii of 30mm can be reached without fibre waviness or buckling when sufficient support and forming pressure is provided. However when thicker tri-axial non crimp fabrics are used instead of the combination of bi-axial and UD used in this study, the prevention of inter-ply slippage due to the stitching of plies will likely result in bigger minimum radius of curvature without material defects. It becomes clear that choosing a fibre structure for manufacturing of TPC WTB's will have a significant influence in the extent of reshaping possible at end-of life of the blade.

5.3 Reshaping performance and reshaping method
The vacuum bag forming method used in the experiments has shown to create avoidable material defects. Similar to industry standard thermoplastic composite shaping techniques, care should be given to tension the fabric while reshaping in order to avoid buckling and waviness.

5.4 Re-use application and demonstrator

It is demonstrated that an alternative end of life strategy to direct re-use, shredding or fibre separation can lead to meaningful reuse applications. The chosen re-use application, a lamppost, is a high volume application which makes use of the technical value of the waste material. This application looks to be feasible both from reshaping experimentation as from structural calculations. Beyond technical goals, the demonstrator was used as a conversation starter at several fairs and expositions, sparking meaningful discussions and inspiring researchers and people from the industry alike.

5.5 Future work

As mentioned in the introduction this research was of an explorative nature. More detailed material research has to be performed by qualified researchers. Some aspects that might be of interest in future work are:

- Comparing mechanical properties of virgin, reshaped and non reshaped but heated samples.
- Evaluating the feasibility of intentional delamination of sandwich panels to retrieve face plies.
- Reshaping experimentation of sandwich panels
- Reshaping of thicker face plies and heavier fabrics. Preferably tri-axial as this is closer to the industry standard for wind turbine blades. Different orientations of plate,

both in fibre direction in relation to the mould and which side is facing the mould should also be experimented upon

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