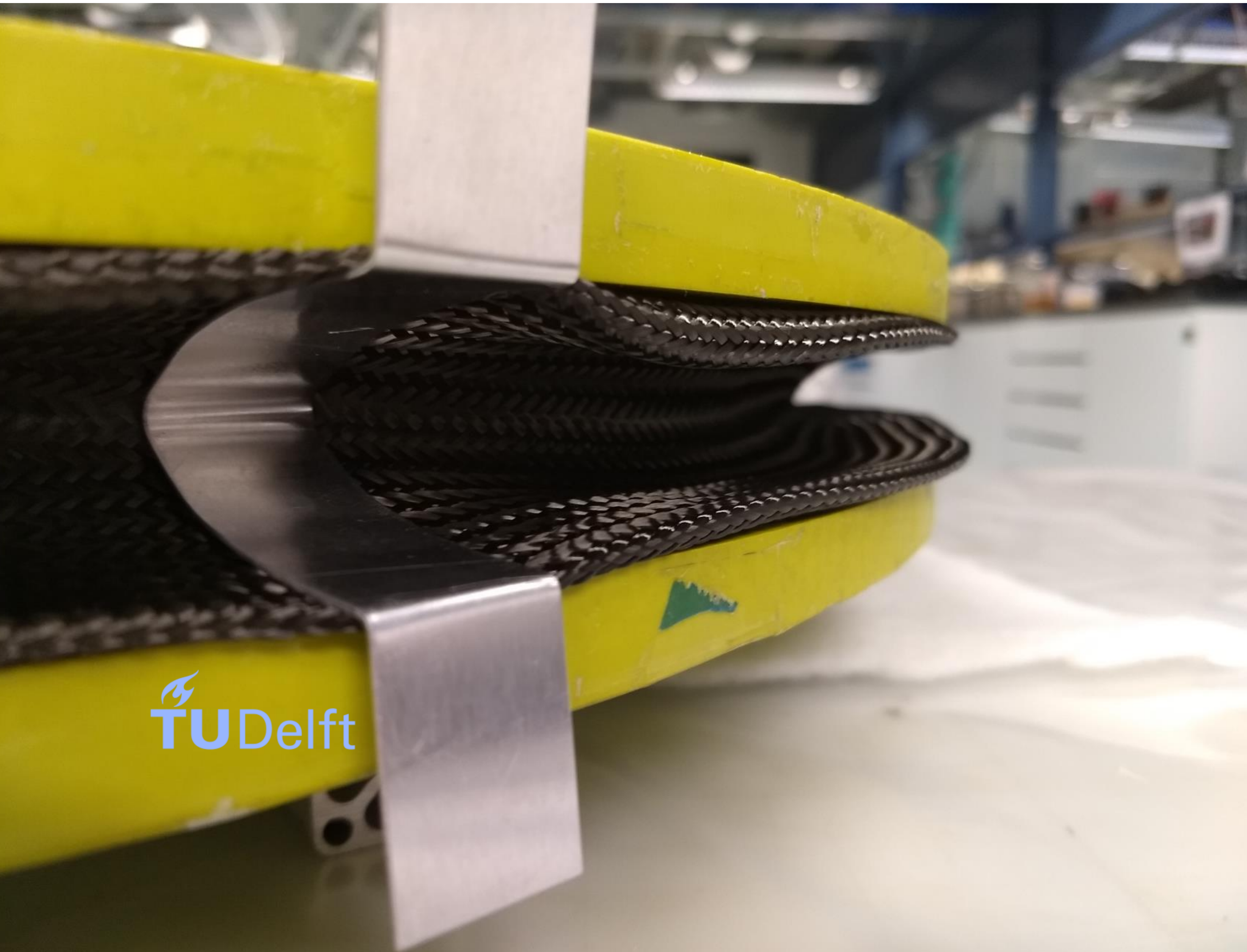
S.J.J. Zuurendonk

Carbon Fibre Composite Rim

Manufacturing Automation Study



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Carbon Fibre Composite Rim

Manufacturing Automation Study

By

S.J.J. Zuurendonk

in partial fulfilment of the requirements for the degree of

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Abstract

This report shows the intended process to automatically manufacture Carbon Fibre Reinforced Thermo Plastic (CFRTP) double bend frames. Bicycle rims were chosen as a scaled down representation for difficult to manufacture double bend products. Fuselage frames require a too large facility. The aim is to manufacture CFRTP products in an automated process, with lower cost compared to current methods. Local automated production minimizes transport costs, increases the control over the quality of the product and the production process compared to outsourcing to low income countries. This would increase the grip on quality, lower the necessary transport and create a more economical solution.

The scope of this thesis was to tackle the automation and manufacturing difficulties of double bend products. Braids were evaluated as a solution, which proved to be usable for automatic manufacturing. In order to achieve full automation, the main manufacturing issues are correlated to design details of the product. These details need proper production equipment and optimized processes in order for quality to be consistent.

Braids were tested for automation and were found to be very successful with respect to simplicity of forming. A rim was manufactured using braids only, together with a thermoset matrix. Applying a thermoplastic matrix would be a logical next step, and could mean further advancement in automation of carbon fibre products.

1. Introduction

In the aerospace world every gram matters. Composites combine the necessary strength and low weight that is highly valued in the industry. More and more parts are manufactured out of composite materials instead of aluminium. The Airbus A380 uses GLARE for the wing leading edge and a carbon composite vertical tail structure (Jerome, 2006). The Boeing 787 is made from 50% composite materials, including the wing and the fuselage (Hale, 2006). These are very large and important components. Other parts that could be made out of composites are bulkheads, stringers and structural beams. Manufacturing these components using carbon fibre is an expensive and a labour intensive process, due to the material involved, long cycle times and manual labour. If the production could be automated and implemented locally it would mean less transport, thus reducing cost and decreasing the required energy. Quality control would also be enhanced, since manual labour is less accurate and prone to mishandling of the material during production compared to an automated process. Therefore, in order to make the production of carbon fibre products more achievable locally, a new process is researched.

Producing airplane components is a large undertaking, therefore a racing bicycle rim is used to adjust the scale of the manufactured products to something more manageable during this research project. Using carbon fibre in an automated manufacturing process for bicycles gives its own set of advantages.
Having the lightest frame and set of wheels is a must in the bicycle racing world and lowering the total mass of the system results in less energy needed to move forward. Carbon fibre rims can give a competitive edge and even the casual biker at some point wants to optimise their equipment and invest in the lightest wheels. At this point in time carbon fibre rims are an expensive investment for most and automation might be a solution to decrease the price and increase sales. Therefor using the carbon fibre rim as a starting point to research automation seems to be a valid strategy.

A high bicycle rim has a double bend curve which is a difficult shape to manufacture. There are also similarities with frames and stringers used in pressure vessels. If it can be shown that a rim like this can be automatically produced, the process can be translated for aerospace use. Figure 1 shows the dimensions of a standard racing bike rim and an aircraft fuselage to emphasize the scale difference.

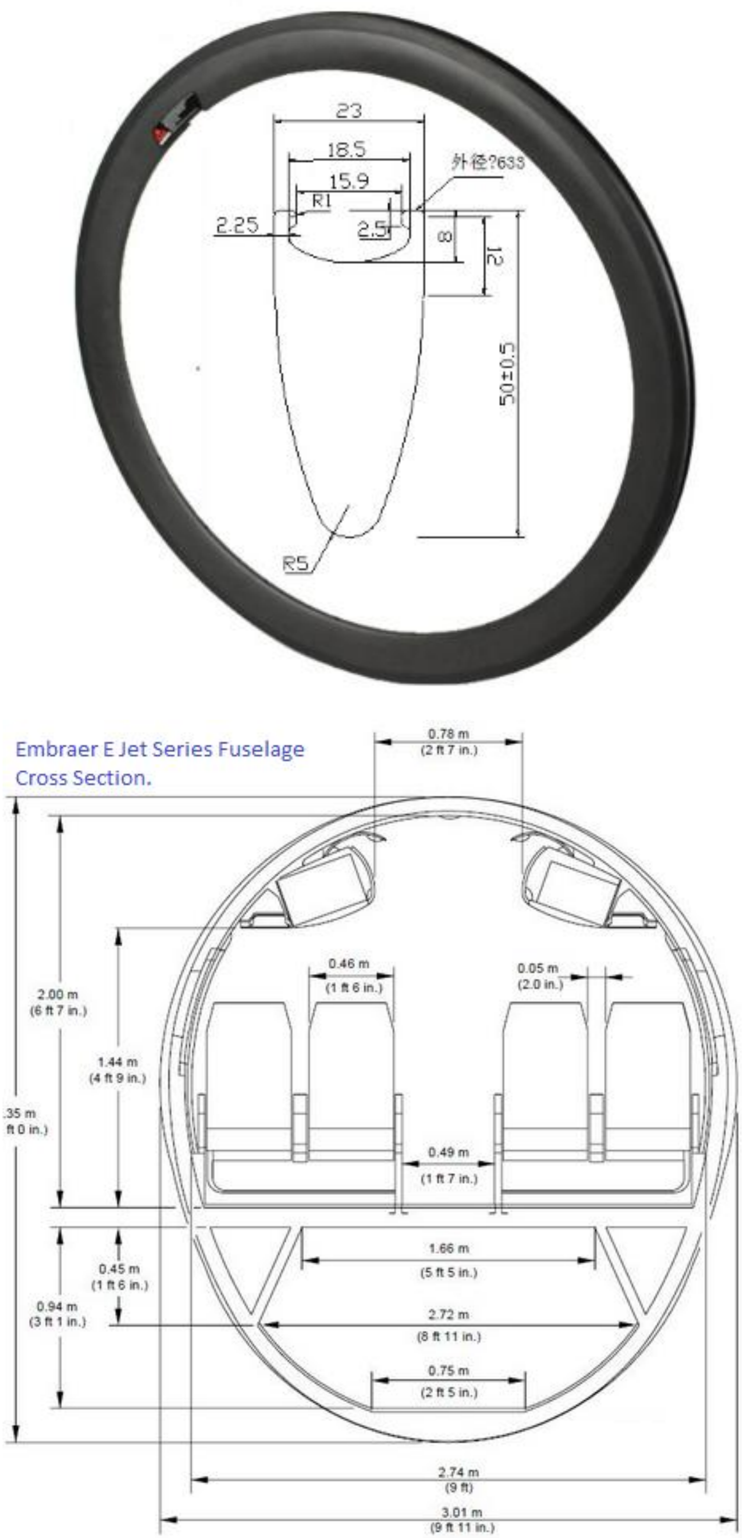


Figure 1: Current design of the Carbon Racing rim with the dimensions given in millimetre (Doevendans, 2016) and the dimensions of the fuselage of an Embrear Jet for comparison in scale (Modern Airliners).

The baseline rim is defined first, the dimensions are as follows (Doevendans, 2016):

- Type: Tubeless
- Outer Diameter: 633mm
- Width: 23mm
- Height of the rim: 50mm
- Spokes: 24

This research will show the possibilities for the automation of the production of a carbon fibre reinforced polymer rim. The goal is to explore the mechanics and methods that are currently available and devise a process that automates production. At this point in time the focus lies on forming double bend curves, but other aspects for manufacturing rims will be kept in mind during the whole process.

1.1 Objectives and Sub-goals

The hypothesis of the research is that thermoplastic composites together with roll forming is a feasible combination to automatically manufacture double bend shapes. In the second chapter, more detail is provided regarding the difficulties and the manufacturing techniques that helped shape the sub questions. The shaping properties of thermoplastics could reduce production times and cost. Thermoplastics can be heated to their processing temperature and then shaped, with less difficulty compared to the impregnation and curing needed with thermosets. If it can be shown that thermoplastics can be used for the same purposes as thermosets, production does not have to resort to using low income countries. When production is automated in a local factory, transport can be minimized; costs can be cut down heavily and the overall production process could become more sustainable.
The leading question is formulated as follows:

What would be a viable fully automated production process for double bend carbon fibre reinforced composites?

The leading question, together with the intended process, gives rise to certain more detailed sub-questions that will need to be researched and tested.

Questions regarding material:

- Are thermoplastic composites a feasible alternative to thermoset composites?
    - Can thermoplastics withstand the temperatures in racing bike environments?
        - Are there ways to divert the dissipated energy away from the rim?
    - What are the mechanical property differences?
        - Do the differences in mechanical properties have a substantial influence on the design of the wheel?

Questions regarding forming:

- Does the deformed reinforcement exceed the strain limitations that prohibit manufacturing?
- Is roll forming thermoplastic carbon fibre sheets feasible?
    - Are double bends possible?
    - Is it possible to keep the material at the needed temperature during forming?
    - Does the shape retain after being released from the mould or does it need a reflow stage in an autoclave for the residual stresses to reset?

- Will the process be feasible when applied to high end thermoplastics and their increased processing and melting temperatures?
- Are multiple forming stages needed in order to properly shape the thermoplastic and if so, how many?

Questions regarding bonding:
- Is fusion bonding as strong as a co-cured product?
  - Is stiffness on par with respect to one part?
  - What is the percentage of load transferred between parts with no continuous fibres?
- Is bonding with adhesives or epoxy strong and stiff enough for racing bike load scenarios?

Processes deforming thermoplastic based composites require elevated temperatures. The forming of the reinforcement itself is not dependent on temperature. The first tests involve dry fibres, later tests the dry fibers are infused with epoxy resin by vacuum infusion. This is done to separate the forming difficulties and the difficulties caused by needing an elevated temperature. Vacuum infusion requires less sophisticated equipment compared to thermoplastic roll forming and is readily available. If the shape is possible in thermoset epoxy, it can be directly translated to a different matrix with the right manufacturing process. The process step that is thought to be critical for automation is bending the cross sectional beam (more detail on this in chapter 3, Phase 1: Step 3). Therefore the objective for the thesis is to be able to double bend a singular piece of carbon fibre composite in a circular double bend shape to prove a component of the conceptual production process outlined in chapter 3.

In order to achieve automation, the limitations of current techniques and the common issues with respect to manufacturing with carbon fibre need to be identified. When a better understanding is formed on current production processes and material, a preliminary process design can be designed. The preliminary process can then be used to identify potential problems during forming that need to be tested.

From literature a preliminary process was derived, as can be read in chapter two. First the main forming issues and difficulties for carbon fibre products are explained. Deformation and tooling phenomena, joining of parts and things for consideration are also shown. Then the processes that are used to manufacture general rims are shown and explained. The processes that are currently in use to automatically produce carbon fibre products are then listed and scrutinized with respect to automating the production of a double bend product. Chapter three explains the preliminary process to automate production, a process that involves the plastic deformation behaviour of thermoplastics and their processing benefits together with roll forming. The steps in the process that are deemed critical for automation are explained in this chapter as well. Chapter four shows the testing that has been done in order to answer the research questions, as well as the results and the conclusions drawn from those results. At the end of every test there is a discussion in order to reflect on the methodology and the outcome. The planning on how the testing has been done is also explained here. In chapter five conclusions are drawn with respect to automation and the tests. Chapter six contains the recommendations for future research.

2. Literature Review

The literature review will explain the difficulties that arise when manufacturing a carbon fibre product. Section 2.1 shows and explains some of the general difficulties that occur and that have to be kept in mind during the forming and production of carbon fibre products. Section 2.2 has information on thermoplastics, thermosets and their properties. Section 2.3 explains the need for a hollow cross section and what options exist to achieve said hollow cross section. Section 2.4 shows the methods that can be used for bonding two components together, since the preliminary process requires two components to be brought together. Section 2.5 shows the manufacturing processes that are used currently to automatically produce rims. Section 2.6 shows carbon fibre manufacturing techniques that are interesting for automation and that have been utilized for the preliminary automation process. The advantages, disadvantages and the automation aspects, with respect to the manufacturing of a bicycle rim, are explained for each technique. The chapter ends with Section 2.7 which shows the current production steps for a carbon fibre rim.

2.1 Shaping and forming

When manufacturing and shaping with fabric based composites, there are certain difficulties. Figure 2 shows an overview of several interface and intra-ply mechanics that can occur during manufacturing using moulds. These phenomena appear in every manufacturing cycle and taking these interactions into consideration can improve the quality and effectiveness of the automated process. In this section the several manufacturing phenomena are explained.

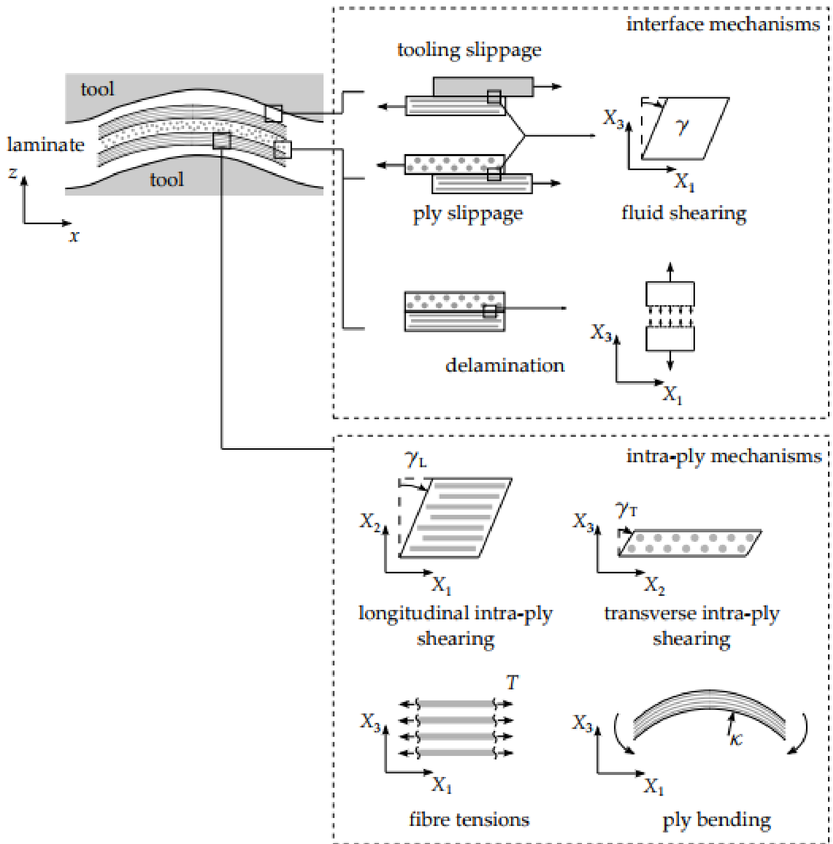


Figure 2: Tooling interface mechanisms that occur during production as well as ply-tool interactions that cause inter- and intra-ply deformations. (Haanappel, 2013).

2.1.1 Inter-ply shear

Inter-ply shear, see figure 3 (Erland, 2015), introduces spring back and residual stresses that could cause creep or delamination in the part. When manufacturing with composites, plies move with respect to each other in order to be able to conform to shapes. When using thermoplastics inter-ply shear results in residual stresses due to the matrix being deformed, but wanting to return to its original shape. In an automated process, these discrepancies and misalignments need to be considered.

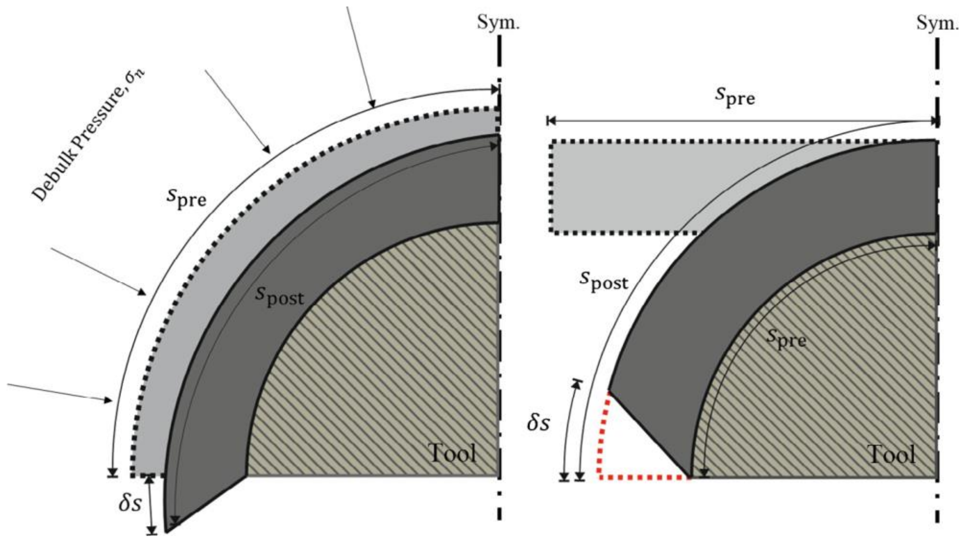


Figure 3: Inter-ply shear, a type of shear that occurs when plies/layers within a layup move relatively to each other due to forming/manufacturing. Left: When layers are placed on the mould and pressed against it the separate plies move with respect to each other to accommodate for the change in circumference. Right: When layers are folded over the mould. (Erland et al. 2015)

2.1.2 Trellis effect

The Trellis effect, as can be seen in figure 4 (Yu, 1994), occurs when different directions of the fabric undergo a different load, for example during production of double bend curves. According to Bergsma (1988), the maximum deformation angle is around 30˚ for most fabrics, which corresponds to approximately 25% elongation and a 30% reduction in width of the fabric.

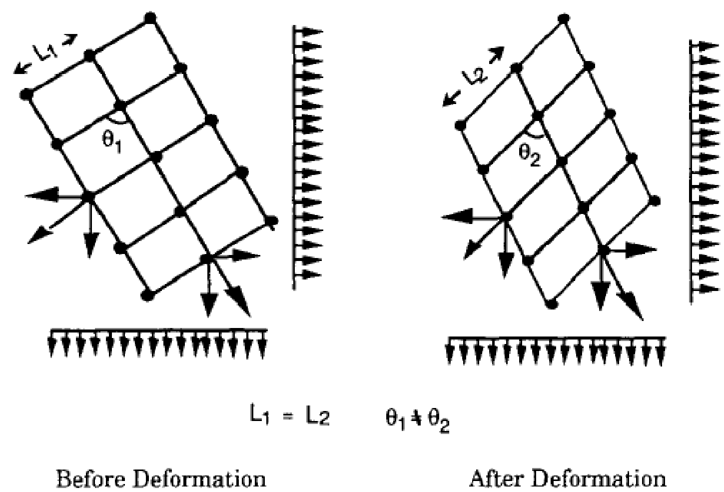


Figure 4: The Trellis effect is a fibre deformation where fibres change mutual directions without stretching. The 'maximum deformation angle' defines the limit of the fabric's shearing capabilities. The maximum deformation angle is limited by the local buckling of the fibres when compressed. (Yu, 1995)

2.1.3 Intra-ply shear

Intra-ply shear, see figure 5, is prevalent in the rim since the inner radius of the rim is significantly smaller than the outer radius, resulting in strain differences that result in shearing of the sheets. (Stanley and Mallon, 2006)

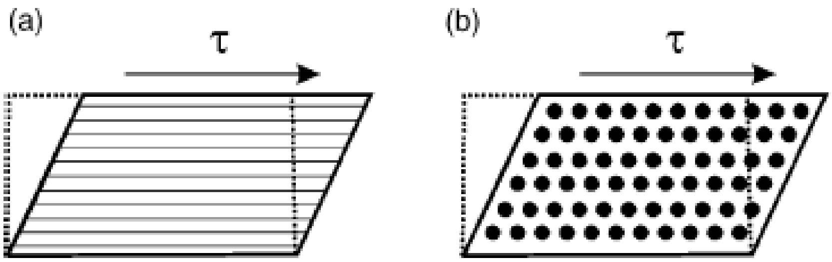


Figure 5: Two modes of intraply shear in unidirectional composite materials, occurs during manufacturing of parts out of sheet material when the separate fibres have to shear with respect to each other and change orientation with respect to each other in order to produce wrinkle free products: (a) axial or longitudinal and (b) transverse (Stanley and Mallon, 2006)

2.1.4 Strain

Strain is stretching of the fibres when force is applied. The maximum strain for fibres lies between 1-3% (Mallick, 2007). This causes forming issues when the inner and outer radius differ more than what the fibre can stretch, resulting in wrinkling and/or breaking of the fabric to cope with the strain.

2.1.5 Fibre warping

Fibre warping, see figure 6 (Behrens, 2017), is an issue when dealing with products that have an altering cross section, or when excess material is pushed back into itself without restraining moulds. It is comparable to buckling.

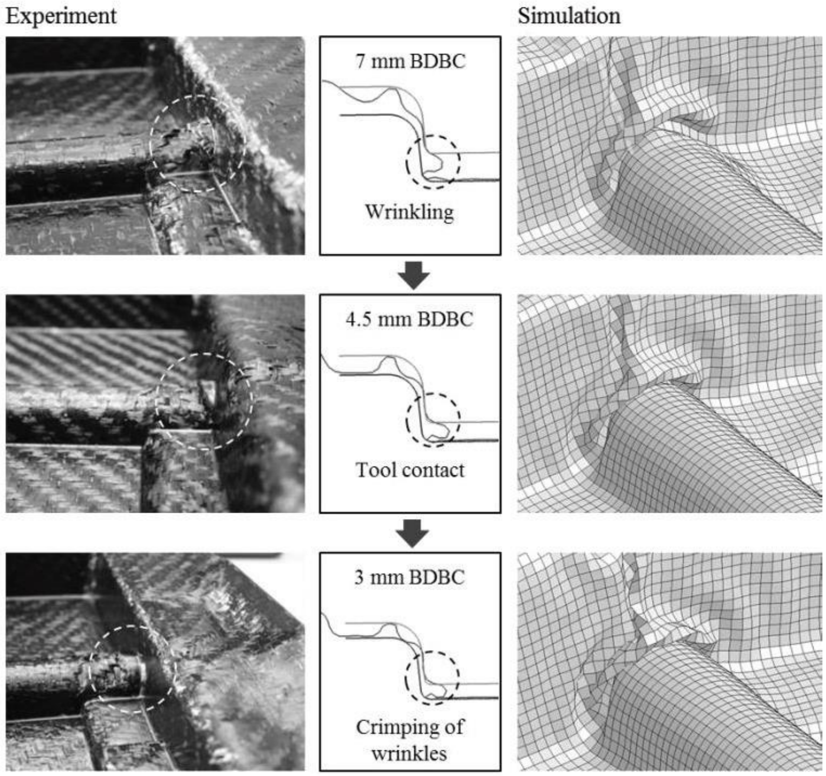


Figure 6: Fibre warping occurs when the fibre moves in the direction perpendicular to the main straightened fibre direction. The images show a series of wrinkling behaviour around multiple bends (organic sheet 0/90°) (Behrens, 2017).

2.1.6 Shear slip

Figure 7 shows several instances of shear slip in a multi-depth part, where the fabric deformation allows for shape conformation.

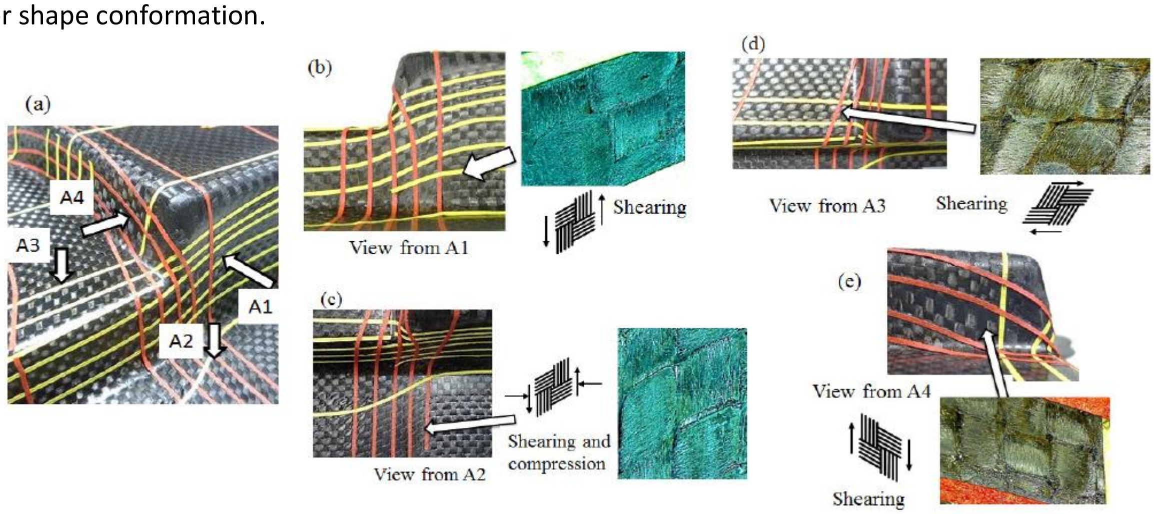


Figure 7: Shear slip is the deformation that occurs when the fibres displace in transverse direction within the plane of the fabric. Essentially loosening or tightening of the fibre bundles during handling of the material or when forming around contours of a product. Shearing of fabric on a multi-depth carbon fibre fabric product (a) Overview, (b) view from A1 (c) view from A2, (d) view from A3, and (e) view from A4. (Hineno et al., 2014)

2.1.7 Transverse flow

Transverse flow, see figure 8, is an issue when using uni-directional thermoplastic prepregs that are thicker than the final product. During automation it is possible that parameters are not designed or programmed properly, thereby applying too much pressure on the material causing this type of phenomenon.

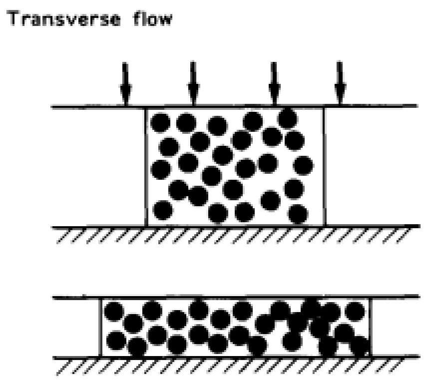


Figure 8: Transverse flow occurs when a compressive force is placed on a thermoplastic fabric. The material will be compressed and fibres are pushed out of position. This requires the matrix to be able to flow. Shown here composite before and after compression. (Barnes and Cogswell, 1989)

2.1.8 Percolation

Percolation is when excess thermoplastic material has to be forced through the fibres in order for the product to be able be produced. It heals flaws and allows bonding of pre-impregnated tape. In order to achieve full consolidation of a stack of plies, excess resin is needed to form a resin rich interlayer. This phenomena can be useful for automation, since it can heal imperfections that occur during the production process. However, the extra material also has to be removed in a later stage and can clog up tooling. (Barnes and Cogswell, 1989)

2.1.9 Double bends and domes

Manufacturing double bend parts or dome shapes come with difficulties, as can be seen from multiple tests done by others with thermoplastic fabric. When forming thermoplastic sheets into square cups (figure 9), the sections where the cross section is constant provide little problems. It is when a cross section changes that the fibre and the fabric have difficulties to conform to the shape. The change in cross section causes shearing of the fibre angles, as can be seen in figure 10. (Wang et al., 2013; Alshahrani and Hojjati, 2017)

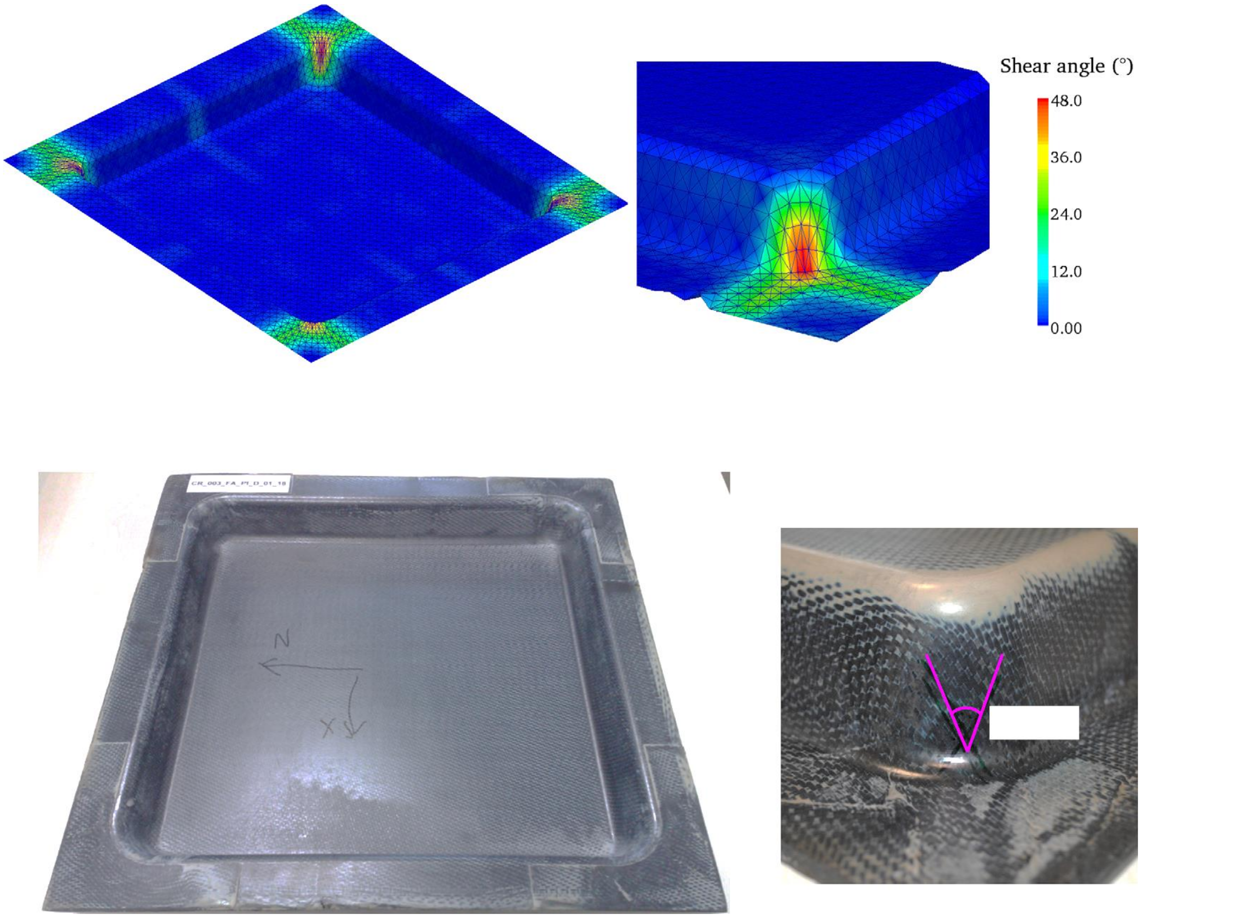
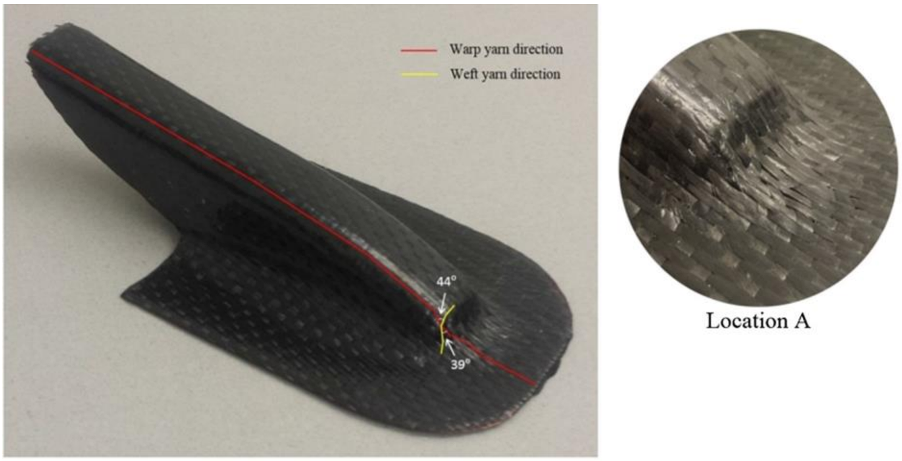
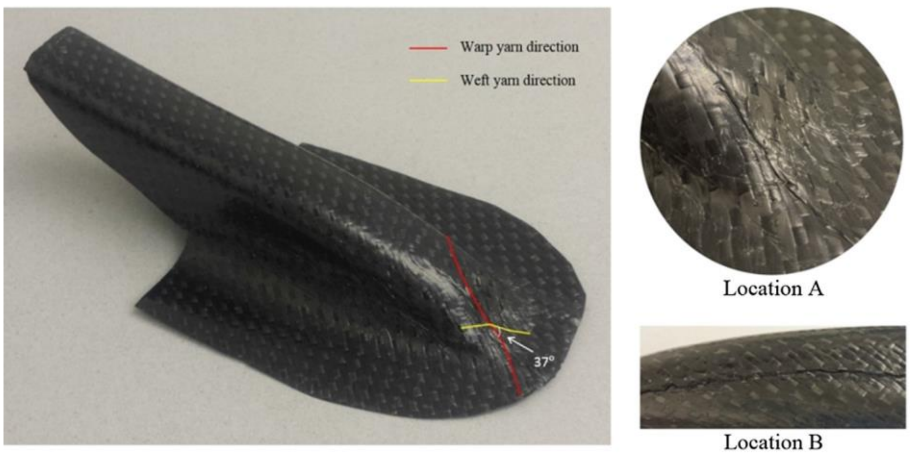


Figure 9: The corners of a formed thermoplastic cup shows shearing of the fibres in order for the fabric to be able to comply with the shape. Left to right: (a) Shear angle distribution in the composite part (simulation), (b) maximum shear angle in ply 7 (simulation), (c) final composite part, and (d) maximum shear angle (Wang et al., 2013)



(a)



(b)

Figure 10: A changing cross section of a part protruding from a flat surface. It shows how the fabric deforms in order to conform to the shape that is wanted. The fabric on the top of the part forms well, but the remaining fabric shears in order to be able to cope with the changing cross-section. Forming results for single ply: (a) warp yarn direction is aligned with the x-direction, and (b) warp yarn direction is rotated by 45 with respect to x-direction. (Alshahrani and Hojjati, 2017)

When looking at the rim in this research, the difference in circumference in outer and inner radius and the double bend are what cause most of these production and manufacturing issues. Either the inner radius wrinkles, or the outer radius stretches with respect to the neutral axis of the shape that is formed (Ropers et al., 2016; Nienhuis, 2005). Carbon fibre has very low maximum strain values, around 1-3%, therefore this would be an issue. The definition of the neutral axis can be seen in figure 11. However, this standard definition of the neutral axis is valid for cross sections made out of solid materials where the neutral axis coincides with the geometrical centre of the cross section. Due to the fact that fabric is used, the neutral axis is dependent on where the forming loads are applied onto the fabric. If the placement forces are focussed on the bottom of the fabric, the top part will stretch if the material allows. If the placement forces are at the top of the rim, then the inside will wrinkle and buckle to accommodate for the strain differences. (Ghalghachi, 2016).

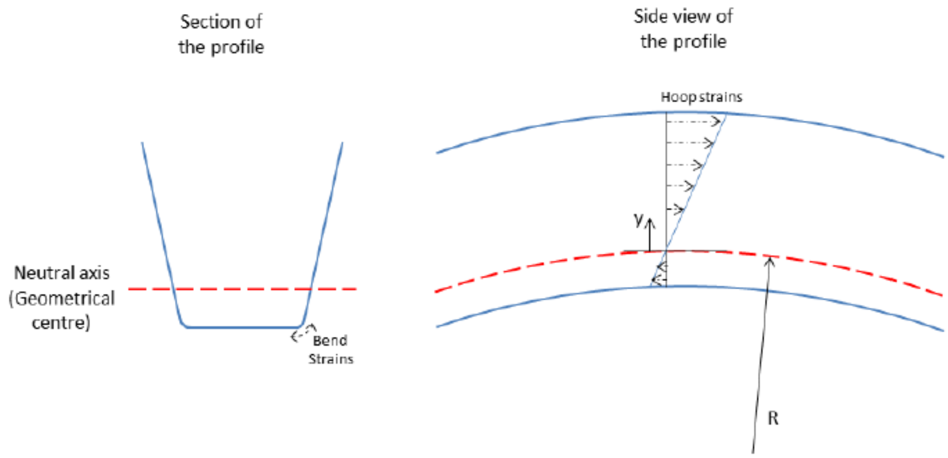


Figure 11: Definition of neutral axis and profile for the bicycle rim, valid when the red line is the base from where the forming is done (Ghalghachi, 2016)

Depending on the distance from the neutral axis, the fabric will shear and the angle between the different directional fibres changes, this is called the shear angle. The shear angle of a weave is given by Equation 1 (Ghalghachi, 2016):

Equation 1: shear angle

$$\varphi = \text{Arccosinus}\left(\frac{\sqrt{2}}{2}\left(\frac{y}{R} - 1\right)\right)$$

Where y is the distance from the neutral axis and R is the radius of the rim. Using the rim height of 50 millimeters and the rim radius of 316.5 millimeters in the formula, this means that the shear of the weave will lead to a 30 degree angle at the top of the flange, for an example of this phenomon see figure 12. (Ghalghachi, 2016)

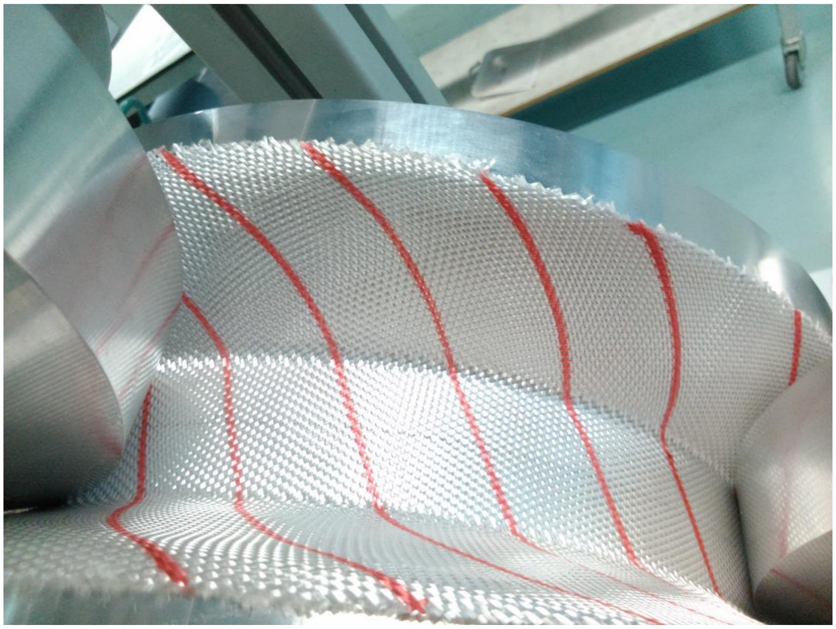


Figure 12: Warping of fibre orientation after forming the fabric into a circular shape. The red lines show the change in direction and the angle that the fibre go through in order to comply with the difference in circumference. (Ghalghachi, 2016)

2.2 Thermoplastics and Thermosets

In order find out which material to use, thermoplastics or thermosets, the general differences, advantages and disadvantages are laid out in this section. The reader is directed to appendix A.1 for more information.

Thermoplastics inhibit a glass transition temperature, this gives them the property that after heating them beyond this point they become more mouldable with temperature and can be reshaped. This trait can be used for automation, since the material does not change in between heat cycle apart from its shape.

Thermoset resins are composite materials that have low viscosity during production and then cure into a solid over time. Most high volume production is done with pre-impregnated fibres. These are sheets of carbon fibre that already have the resin pre-applied and only need a curing cycle to harden into the final product. They require expensive autoclaves for the best results. There are also Out-Of-Autoclave (OOA) prepreg materials (Gardiner, 2011). These OOA prepreg sheets can be cured in ovens between 70°C and 130°C, with only the need for a vacuum instead of high pressure (Centea et al, 2015). All pre-pregs are malleable at room temperature and can be shaped accordingly. After the necessary plies are laid, the mould is vacuum bagged and put into an oven, where the resin cures and the product is finished. Considerations that have to be taken into account when using OOA prepregs is that one has to take care for voids due to the nature of the sheets and the reduced pressure at which the curing cycle is done.

2.3 The hollow cross section

In order to enhance the torsional and bending stiffness of the rim, and in order to save weight, a hollow section is added to the cross section. Figure 13 shows a rim with a hollow cross section. This greatly improves the secondary moment of area and with that the bending stiffness of the rim, without sacrificing weight as much compared to making the product thicker. To incorporate a hollow cross section in an automated process is a challenge, but needed in order to have a competitive product. To achieve this hollow section there are multiple possibilities: Using a bladder during production, using a core material that is either removed or stays in place after production, and manufacturing separate components that are joined at a later stage. More information on the bladder and core materials can be found in the appendix A.2.

Figure 13: A cross section of a racing bike rim showing the hollow section on the inside.

2.4 Bonding for thermoplastic products

When manufacturing a product out of multiple parts, they need to be assembled at some point. For thermoplastics the preferred methods are fusion and welding. Bonding by means of an adhesive is acceptable when the product is not part of a main loadbearing structure. More information on these techniques can be found in appendix A.3.

Fusion would give a product that has no bond lines, making it one material that is indistinguishable from a product that was made in a single process. Fusion requires high pressure, heat and the proper tooling to obtain proper results. Welding requires extra material and a conducting mesh for current to flow through. This adds to the complexity of the automation process. Adhesive bonding is not a preferred method, though it could be used as an initial step to automation while other techniques mature.

2.5 Manufacturing

In this section the methods used to manufacture rims in general and regular carbon fibre products are discussed. This is to give an indication of what is currently utilized and what methods are proven to work for certain design choices. The manufacturing techniques that inspired the preliminary process are shown here.

2.5.1 Aluminium extrusion

Aluminium billets are extruded into the shape of the cross section of the rim, after which they get roll formed into a coil with the correct wheel diameter. The coil is separated into multiple rings with a cut and then the loose ends are welded together to create the rim (How it’s made, 2011). This method is automated and requires minimal human interaction apart from feeding the machines in each process step.

2.5.2 Roll forming

Steel rims in the automotive industry are created in a continuous roll forming process, starting with a sheet of metal and ending with a rim. Figure 14 shows a regular roll forming process for a steel car rim.

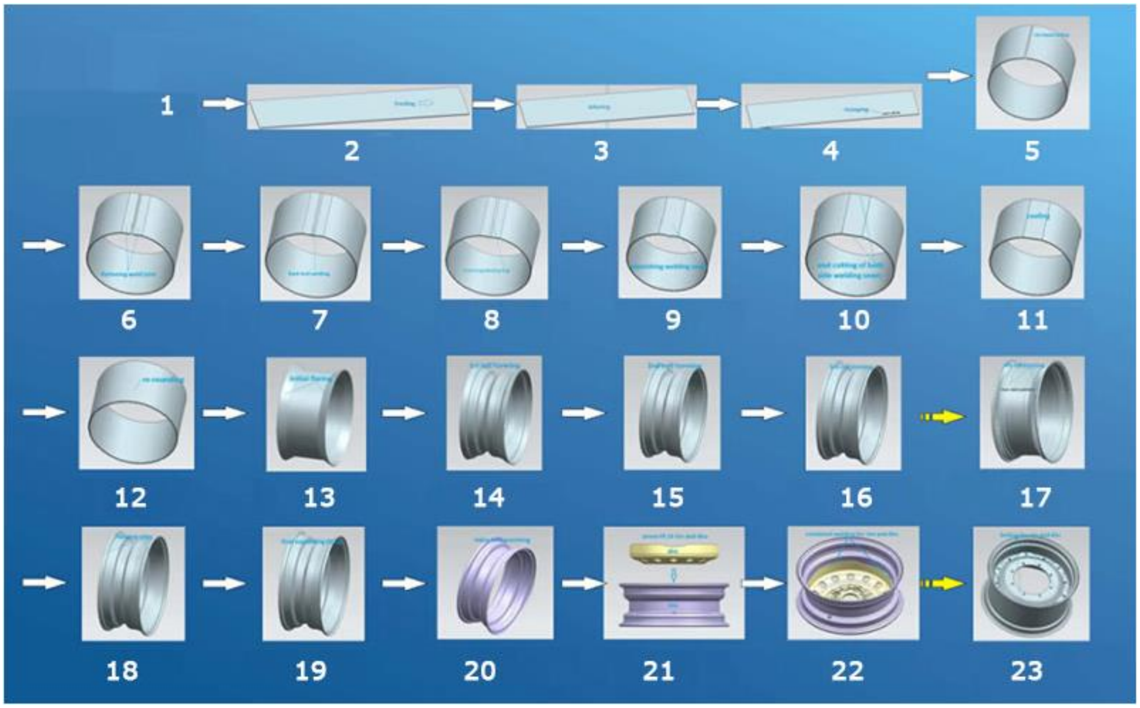


Figure 14: Roll forming process of a steel car rim. 1: Low carbon steel strip cut to length. 2: Rim band feeding. 3: Deburring of both sides. 4: stamping mark. 5: Rim band coiling. 6: Flattening of the weld joint. 7: Flash butt welding. 8: Trimming the welding slag. 9: Planishing. 10: End cutting. 11: Cooling. 12: Re-rounding. 13: Initial flaring. 14: 1st roll forming. 15: 2nd roll forming. 16: 3rd roll forming. 17: 4th roll forming for non-skid pattern. 18: Edge flanging. 19: Final expanding. 20: Valve hole punching. 21: Press disc into rim. 22: Combined welding for rim and disc. 23: Bolting rim and disc. (Wheelmachinery)

2.6 Automation in carbon fibre industry

Currently there are multiple ways of processing carbon fibre into products. They all have their advantages and disadvantages when it comes to speed, quality, price and accessibility. In the next section the several processes that were meaningful to this research and the preliminary process are shown and their respective advantages and disadvantages explained. Afterwards, their relevance towards automating the production process of a bicycle rim is scrutinized.

2.6.1 Over-braiding

Braiding is a technique that braids strands of fibres over a mould, see figure 15 for a typical set-up. At this point in time it is generally used to create products that allow the braid to be pulled over a mould. It is difficult to keep the fibres aligned in the orientation that is designed. Angles of zero and ninety degrees are practically impossible to produce using braiding due to the nature of the method. Braids are also manufactured without using moulds, creating long continuous braids.

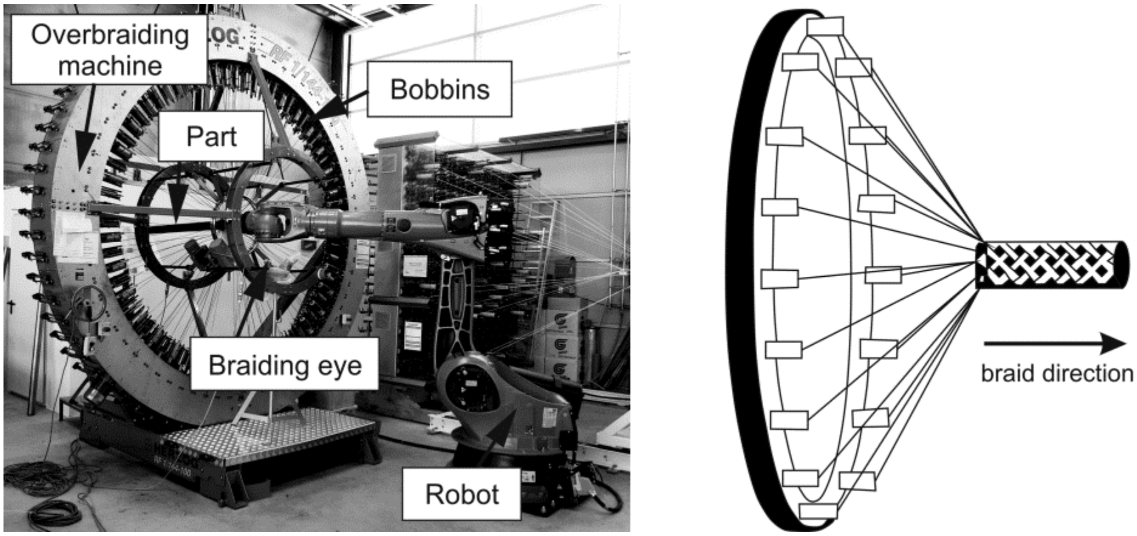


Figure 15: Typical braiding setup. The part is fed through the eye of the braiding machine, where the machine braids the strands of carbon fibre around the part. As can be seen, a large part requires a large machine. (Design)

Advantages:

- The braids are able to conform to shapes of many geometries and sizes on its own due to the shearing of the fabric;
- The production speed of the carbon braid as a product on its own lowers the raw added material costs compared to pre-preg.

Disadvantages:

- The nature of the braiding machine leads to limited fibre angles unless 0/90° fibres are pre-applied and over-braided. The machine itself cannot place 0/90°;
- A lower fibre density compared to pre-pregs due to being a fabric and not separate fibre layers;
- Limited geometry when using the over-braiding machine;
- Complex machine needed for over-braiding;
- Slower overall manufacturing process since pre-forming the part needs to be prepared and the machine needs to be adjusted and attached to the part. Also contributing are the steps needed to get the part out of the machine post-forming, such as cutting the fibres still connecting the machine to the part.

Reflection with respect to rim automation:

- *Braids react well to deformation during forming*
  Due to the woven fabric nature of the braid, the braid is able to cope with quite some deformation during the forming process. The braids have more leniency when it comes to strain differences and shapes, which is a good property when manufacturing double bend shapes. Another positive aspect is that the braids do not have loose ends on the edges of the fabric, so theoretically product details such as flanges or edges could be produced with higher quality.

- *Braids results in a thicker product compared to pre-pregs*

Woven fabric is thicker compared to UD plies due to the fibres being bend and woven instead of being flat. However, woven fabrics tend to have improved impact toughness and delamination properties due to being a weave where crack propagation in the matrix is halted by the alternating fibres, instead of separate UD stacks where the matrix is able to crack without opposition. Figure 16 shows a sketch of UD and woven fabric.

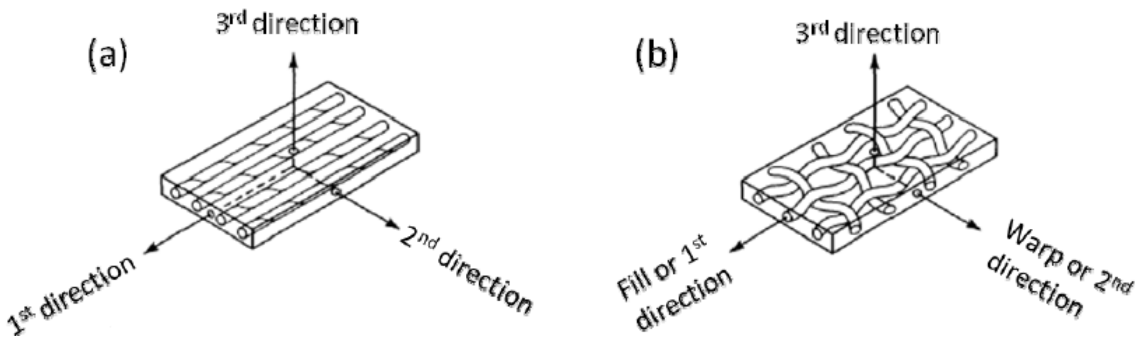


Figure 16: Schematic overview of two fabric types: (a) Uni-directional fibres in a matrix and (b) a plain weave in a matrix. (Joven, R.)

- *The fibre angles tend to warp when the braids are handled during production.*
  Proper automation requires consistent handling and quality control to ensure desired fibre angles are achieved. Fabrics require no force to deform. Since this means that there is also little force needed to deform the fabric into, but also out of, the preferred angles. This is both useful and a detriment.

- *Follows mould features well due to the nature of braids/weaves*
  Weaves and braids follow contours well without falling apart due to the ability for the fibres to slip with respect to each other. For double bend shapes this is a useful feature.

- *Need to add 0/90° weaves/UD plies accordingly for local stiffness*
  Braids are not produced in a 0/90° model due to the nature of the production method. In order to get the required hoop strength and wall stiffness at the wheel bed of the rim, 0/90° weaves or UD layers might need to be added for additional stiffness in the required directions. This is only needed in the top or bottom of the cross-section for increased bending stiffness. The added direction stiffness is unnecessary in the walls, since these are shear loaded.

- *Using the complex over-braiding machine might prove to be very difficult with a bicycle rim.*
  Though there are machines small enough for a bicycle rim to be pulled through the centre, this may not be fully automatable due to the procedures necessary for each braiding cycle.

- *Mass production*
  Braids are mass produced and in a continuous process. This makes the carbon braid relatively cheap when compared to prepreg materials.

2.6.2 Roll forming

Roll forming utilizes the plastic deformation capabilities of a material. Figure 17 shows a typical roll forming process.

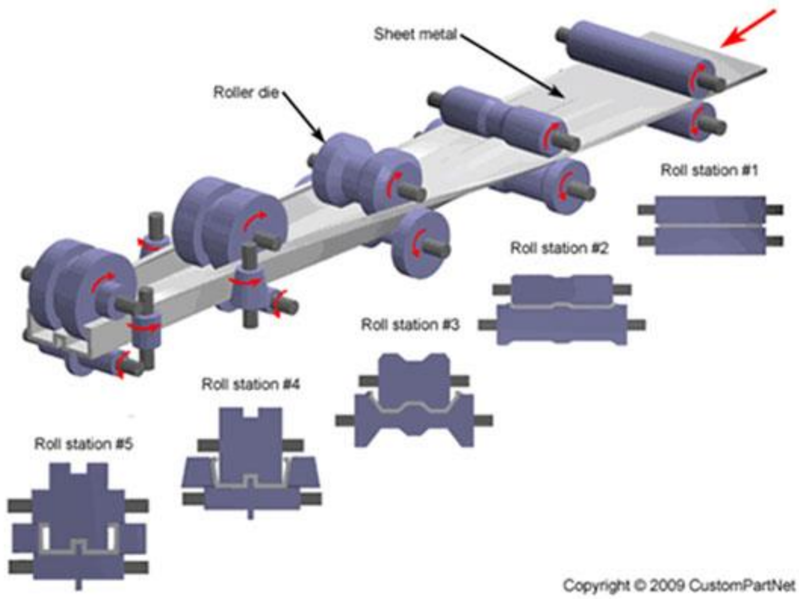


Figure 17: Roll forming is a method where material is shaped by guiding it through a series of double rollers, every station creates a small change in the plates' dimensions and shape by means of plastic deformation.

Advantages:

- The process is relatively easy to automate due to the continuous nature of production and the steps that are performed during manufacturing;
- The cycle time per station is short due to the deformation type and belt fed process;
- Bending in two dimensions, both cross-sectional and curvature.

Disadvantages:

- The shapes that are available for production are limited to open cross sections;
- Multiple stations are needed for proper shaping in order to reduce the stress and strain on the product. Resulting in longer manufacturing lines and the need for more, expensive, moulds.
- The design of proper stations is complex.
- To deform the material the method applies strains in multiple directions and might not be suitable for all reinforcement types.
- The designs for metals cannot be translated directly to composites.

Reflection with respect to rim automation:

- *Short cycle times*

  The continous nature and rolling allows for relatively short cycle times depending on the material properties of the sheet. It may not be as fast for composite materials compared to metals, but with the right matrix material it could be a method to automatically manufacture carbon fibre composite products.

- *Initial investment*
  The rollers are expensive and multiple are needed for each forming stage, resulting in a high series count.

- *Station design*
  Station design can be a tough problem. The stations need to have the right order of bending and forming in order to be able to get the final product.

- *Manufacturing the double bend*
  Using roll forming to create bends can be quite difficult due to strain differences and residual stresses left in the material to be able to permanently deform the composite.

- *The inserted material should preferably be in sheet form*
  In order to use rollforming the inserted material into the rolling dies is preferred to be of sheet material. This means that the layups and fibres need to be prepared beforehand in order for a composite to be formed.

- *Hollow cross section produced by individually rolled components*
  In order to manufacture a proper hollow cross section the product will have to be made out of different produced parts that are connected afterwards.

2.7 Current bicycle rim manufacturing process

The current process of manufacturing the bicycle rims consists of using thermoset carbon fibre prepregs that are cut to size and hand laid into a mould, with overlaps. After the layers are laid down properly a bladder is inserted in order to manufacture a hollow section in the cross-section to save weight and improve stiffness. After all parts are placed, the mould is closed and vacuum bagged. The product is cured inside an autoclave to accommodate for the proper temperatures and pressure. Finally, the product is taken out of the mould, trimmed and then it is ready to get holes drilled for the spokes. After the spokes are integrated the wheel is ready for sale. (Doevendans, 2016; DDCKO, 2017)

The current procedure requires manual labour, long processing times, freezers for the prepregs, expensive material and an autoclave. A flow chart of the current process is shown in Figure 18.

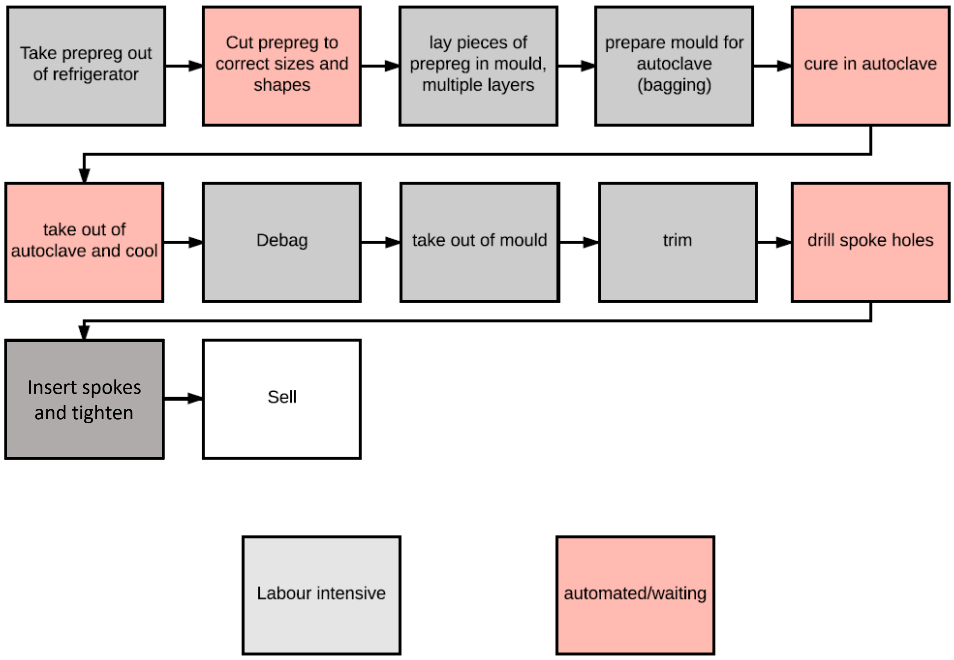


Figure 18: Current process of creating a carbon fibre rim

The wheel that is manufactured through means of the explained process above consists of a regular tubular rim of 633mm outer diameter and with a rim height of 50mm. It has 24 spokes and is made from t700 carbon (figure 19). In the end the new automated manufacturing process will have to produce an equal or better rim to the specifications below.

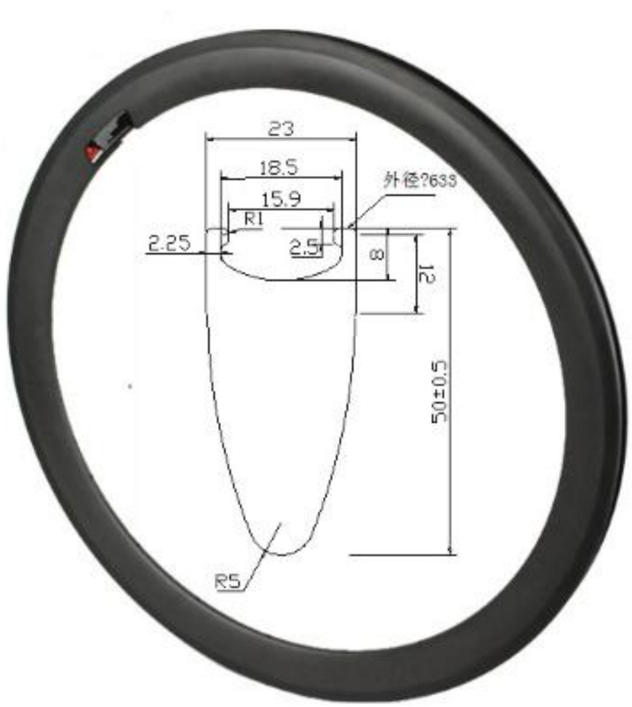


Figure 19: Current design of the Carbon Racing rim with the dimensions given in millimetres. (Doevendans 2016)

Specifications (Doevendans, 2016):

- Type: Tubeless
- Diameter: 633mm
- Width: 23mm
- Height: 55mm
- Effective Rim Diameter: 544mm
- Spokes: 24
- Carbon: T700 @60% fibre volume (Torayca, 2017)
    - Fibre properties
        - Tensile Strength: 4.9 MPa
        - Tensile Modulus: 230 GPa
        - Strain: 2.1%
        - Density: 1.8 g/cm^3
        - CTE: -0.38 alpha e^{-6}/C
        - Specific heat: 0.18 Cal/g*C
        - Thermal conductivity: 0.0224 Cal/cm*s*c
    - Composite properties
        - Tensile Strength: 2.550 MPa
        - Tensile Modulus: 135 GPa
        - Tensile strain: 1.7%
        - Compressive strength: 1.470 MPa
        - Flexural Strength: 1.670 MPa
        - Flexural Modulus: 120 Gpa
        - 90 degree tensile strength: 69 MPa
- Brake edge thickness: 3.2mm
- Brake Surface: Basalt
- Spoke tension: 300kg
- Lateral torsion: 50kg
- Advised rider weight: 95kg
- Rear wheel weight: 920 grams
- Front wheel weight: 740 grams

3. Proposed manufacturing process

A new preliminary production process has been designed taking the literature into consideration. The process is based on utilizing the plastic deformation capabilities of thermoplastics, when they are heated to their respective processing temperatures. After which roll forming is used, just like with metals, to force the CFRTP plates into the desired shape. This method combines a fast and controllable production method with the unique properties of thermoplastics. It consists of two components that are formed at different phases of the production process; the Inner Rim and the Rim well, as can be seen in figure 20.

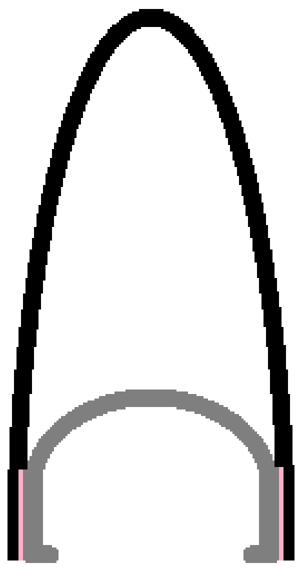


Figure 20: Black:The Inner Rim, Grey: The Rim Wel, Pink: Bonding agent/areal.

The separation of the two components makes it easier to control quality and automate the production. Beforehand the CFRTP sheets can be manufactured into the respective layup that is desired.

3.1 Phase 1: Manufacturing of the inner rim.

The first phase is manufacturing the inner rim and turning it into a coil. Figure 21 shows what the cross section of the finished product in the first phase looks like.

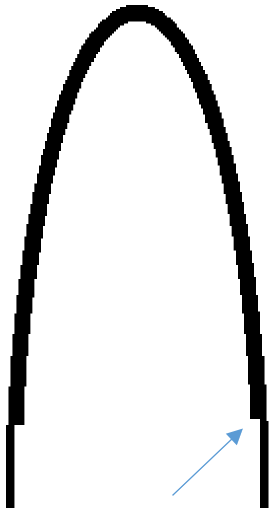


Figure 21: The inner rim with the indentation on which the rim well can latch into and giving an area for bonding.

<u>Step 1: heating the pre-produced thermoplastic plates</u>
The thermoplastic composite pulled through an infra-red oven, see figure 22, to reach the processing temperature. Since thermoplastics tend to cool down rapidly after being heated due to the thinness and the area of the plate, the forming station has to be in or right after the oven. Preferably the moulds should be heated as well.

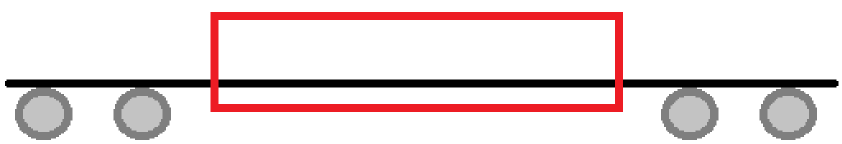


Figure 22: Conveyor belt with an infra-red oven (red box), the plate is fed through the oven in order for the composite to reach the processing temperature.

<u>Step 2: roll forming the inner rim</u>
After heating the plate it can be formed into the first inner part of the rim, still in a straight line to decrease the complexity of the forming tools and the forming forces that the material undergoes. Breaking up the forming process into two allows for the process to be more controlled. The rolling wheel has an extra small lip attached in order to create a pocket for adhesive and an edge for the other rim part to latch onto in order to ensure the right placement, see figure 23.

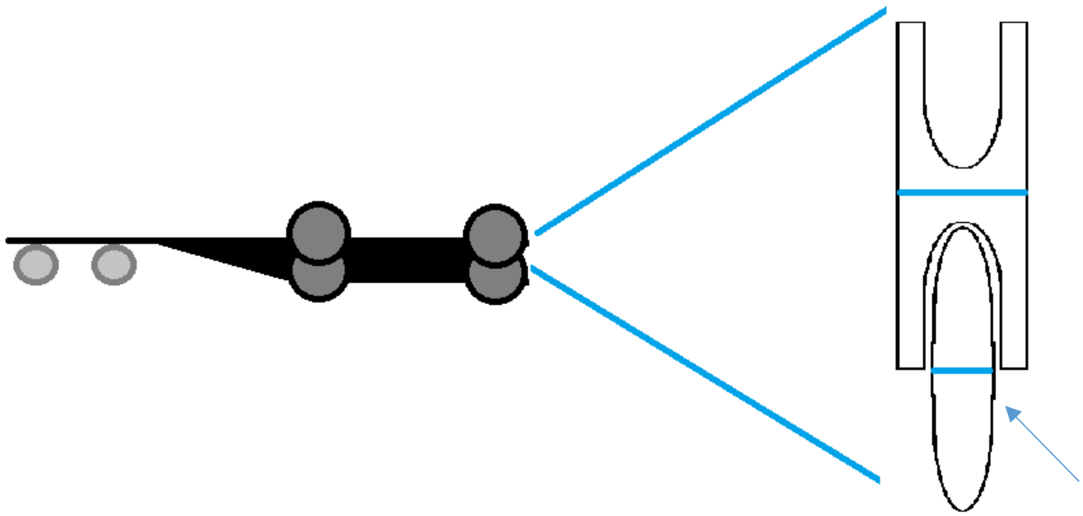


Figure 23: Side view of the first rolling stage: the heated plate is pulled through a series of rollers, the grey layered circles, to manufacture the U-shape of the inner rim. On the right a cross section of a rolling station with an arrow pointing to the extra indentation for bonding. The blue lines are the axis of the rollers.

Step 3: rolling the double bend curve

After the base shape of the inner rim is formed, it gets pulled further by the rollers that will turn it into a rim with the proper diameter. Pulling ensures that the reinforcement in the thermoplastic matrix will not buckle in between rollers and the formed rim slides over a metal mould to support the shape. The thermoplastic should be formed and cooled after about a quarter of the wheel, at the end a roller will push the formed shape sideways to form a coil, comparable to aluminium forming of rims. See figure 24 for a front and side view of the coiling process. Roll forming results in a very fast, continuous production process where the quality and specifications of the product can be monitored properly.

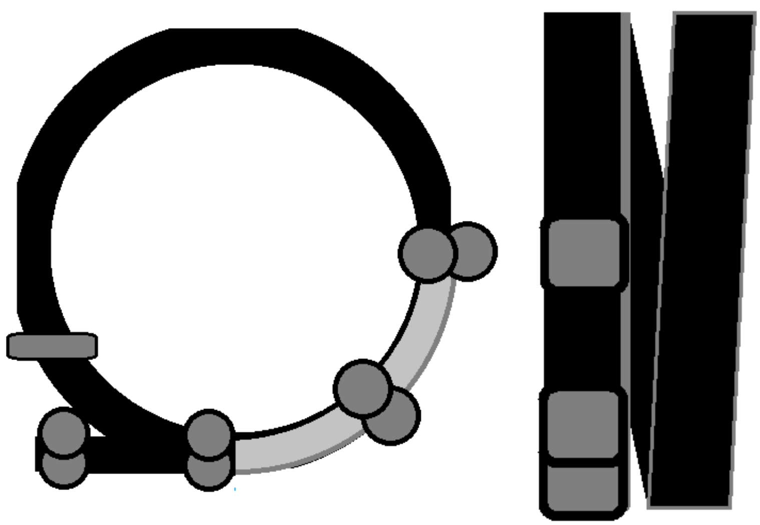


Figure 24: To the left, side-view of the coiling process with three pairs of forming rollers. The dark grey components are rollers, the light grey is the metal sled. To the right, a front view of the coil.

3.2 Phase 2: manufacturing the rim well

Phase 2 manufactures the rim well that is to be inserted and bonded to the inner rim. Most steps are the same as in phase 1, apart from step 3. Figure 25 shows the cross section of the rim well with the indentation.

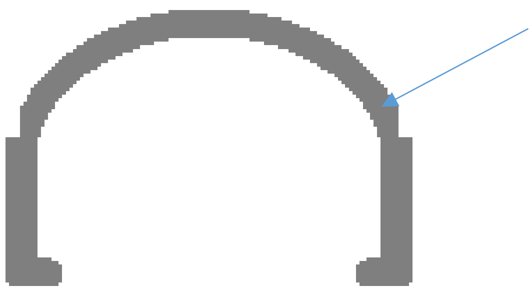


Figure 25: The rim well with the indentation that latches onto the inner rim.

<u>Step 1: heating the pre-produced thermoplastic plates</u>

Start by heating the thermoplastic composite in an infra-red oven, see figure 26.

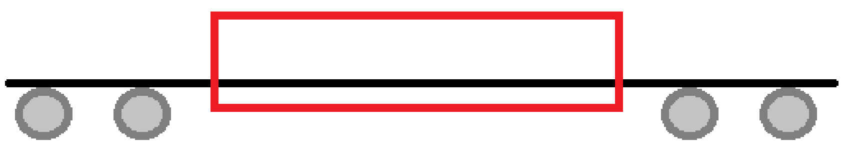


Figure 26: Conveyor belt with an infra-red oven (red box), the plate is fed through the oven in order for the composite to reach the processing temperature.

<u>Step 2: roll forming the rim well</u>

After the plate is heated it gets formed into the proper cross section by roll forming, see figure 27.

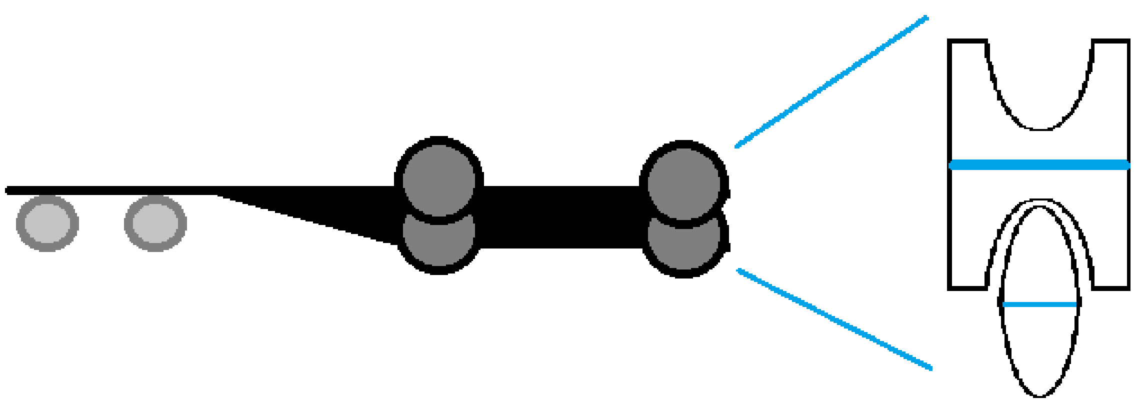


Figure 27: Forming of the rim well. The heated plate is fed through a series of rollers, which are seen on the right, to form the U-shape of the rim well.

Step 3: Feeding the rim well into the inner rim.

This cross section is led into the inner rim cross section in the coil and bonded together, see figure 28. Bonding is chosen for now as it gives the most simple automation step; apply adhesive and use the rollers to apply pressure while the adhesive cures. Welding would require a mesh to be inserted in between the two components, after which it needs current to flow through it for the two components to melt together. Fusion requires an expensive tooling setup that enables the needed heat and pressure for a proper fusion process.

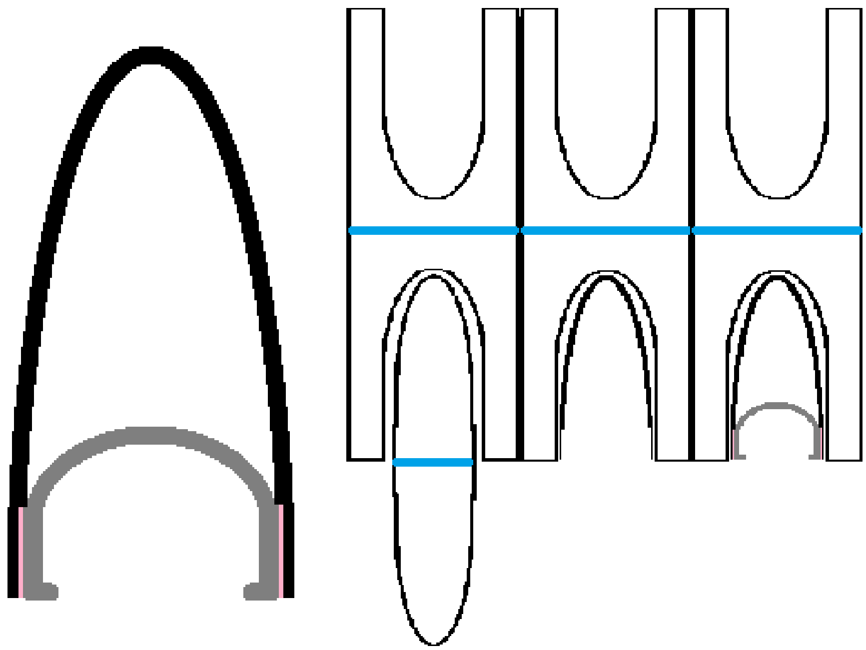


Figure 28: to the left, a cross section of the finished rim with both components joined. To the right, the different steps in the coil; roll forming the inner rim, coiling the inner rim, inserting the rim well into the coil. The right drawing shows the cross section of rollers in parallel, which help form the coil and keep the rim in place for precise joining of the two components. The blue lines represent the axis of the rollers.

3.3 Critical points in the production process

During the production process, certain steps are more critical for the success of the new process than others. Some steps have been proven to be functional, while others are novel and unprecedented. In this section the parts will be scrutinized on their criticality and if they are deemed go or no go.

Phase 1

Step 1:

It is thought that heating the thermoplastic is simple by using an infrared oven. The difficulty lies in keeping the plates at the right temperature during production and during each forming phase, but it has been done in other production processes (Anbuchezhian, 2017).

Step 2:

The forming of thermoplastics is nothing new, as was seen in section 2.1.9. It is thought that this step should be doable and is not that critical, since other products show that it can be done. Thought has to be put into the design of the rolling dies and the amount of stations necessary to minimize residual stresses and strains.

Step 3:
During the rolling of the double bend curve there are problems that could arise. The fabric might not be able to actually form into the shape that is needed, when constructed out of a single piece. This is due to the strain differences between the inner and outer dimensions of the rim and would be critical to the success of the process. The tooling interactions between the roll dies and the composite could result in warping of the weave, resulting in inaccurate fibre angles and therefor lower stiffness and structural fidelity.

Phase 2

Step 1:
As in phase 1, the difficulty lies in ensuring that the plate is kept at the forming temperature during forming phases.

Step 2:
Forming the rim well should not pose a problem in this stage. However, the design details on the rim well need extra roll stations that need to be designed properly.

Step 3:
There are several critical points during this step. First there is the precision needed when placing the rim well into the inner rim. Second there are the uncertainties when using adhesives for bonding. Lastly there is the problem with double bending the rim well and ensuring it does not buckle or wrinkle.

Testing

The step that was deemed both critical and with the highest priority to test is Phase 1: Step 3; forming the double bend. In order for the process to be viable, the shape that needs to be produced has to be possible. The tests that were done during the research therefore focus on shaping and forming a double bend product out of continuous fibres.

4. Tests, Results and Discussions

After determining a critical process step with the preliminary production process, the testing focusses on forming double bend shapes out of continuous fibres. The tests are done to have a better understanding of the rim that has to be produced automatically and if automated production can be achieved with continuous fibres.

The first test was a burn test of the original rim, shown in section 2.7, to determine the layup. From this layup it can then be determined what the necessary reinforcement is for the automatically produced rim. Test two was to see what the impact of the circumference differences was on the formability of a woven 0/90° fabric, and at which rim heights the strain could be resolved by the inherent deformation capabilities of the weave. The third test explored the possibilities of thermoforming thermoplastic composite tapes. The tapes were heated to forming temperature and pressed into a mould, in preparation for roll forming. Test four was done in order to find the effects on a braid when undergoing tensional forming forces. A woven fabric is known to become smaller when under a tensional force, causing deformation due to the trellis effect (Bergsma, 1988), which could be advantageous for controllability of the fabric during roll forming. Tests five to eight are done with braids and thermoset resin infused by vacuum infusion. Braids could allow to manufacture the product out of one component and with more continuous fibres. The goal is to prove that the product can be made mostly out of long combined braids, instead of separate, smaller overlapping layers of pre-preg composite.

4.1 Test 1: Examination of the original layup

The goal of the first test is to see what the original layup of the rim is and to find the types of reinforcement that are needed and where. A piece of rim was cut out of the rim and separated into three parts: the rim well, the cross section wall and the spoke bed. The part that was used for this can be seen in figure 29. The parts of the rim were put in an oven such that the resin could be burned away and the layers could be inspected by peeling away the layers with a pair of tweezers (inside a plastic bag and wearing a mask for safety). The entire process and the used equipment can be found in appendix B.1.

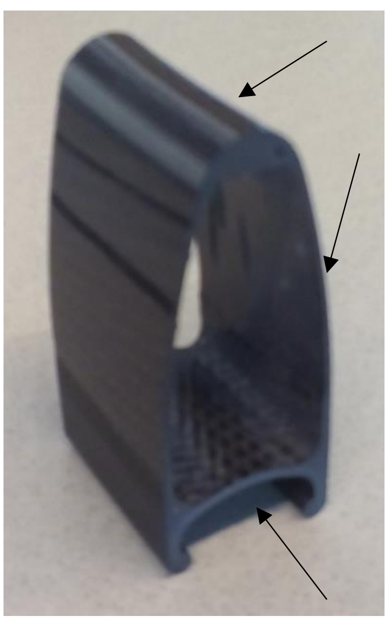


Figure 29: The piece of rim that is cut into three relatively flat sections to be burned in an oven. The arrows from top to bottom: The spoke bed, the side wall and the rim well.

4.1.1 Results

Figure 30 below illustrates the results of the examination and figure 31 highlights what the different parts of the rim looked like after the resin was burned off

Figure 30: The three separate components after burning away the resin, from left to right: The side wall, rim well and spoke bed.

After burning it was found that the rim well consisted of 8 layers of alternating 45° UD, with every two layers a ply of 0°. The wall at the rim well had a single 90° ply of 2cm high, embedded in alternating 45° UD. The corners of the bed, where the tire holds on to, were found to be consolidated 0° strands packed together to form thick wire. The inside of the open section, opposite of the rim well, had a layer of 45° weave.

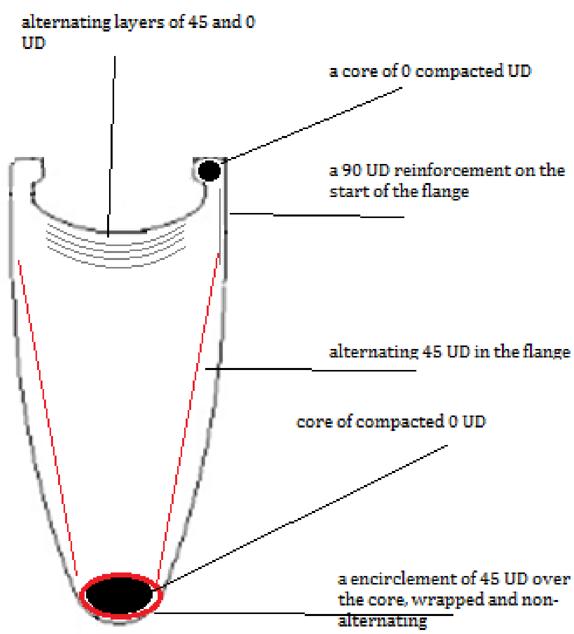


Figure 31: Layup as found after burning away the resin from the reference rim

The flange showed that it was build up out of alternating 45° UD, with an outer show layer of ±45° weave. In total it was 8 layers. The total thickness, which is not specified in the dimensions given by the manufacturer, was found to be around 1.1mm with callipers.

The bottom consists of a core that is build up out of UD strands pressed together and then wrapped with 45° UD. The amount of actual layers was not 100% discerned, but it looked like 4 alternating layers of 45° UD with a 45° weave on the outside.

4.1.2 Conclusion

Different layups were found at different locations, to deal with the altering loads that are present in the cross section. There is no 0/90° reinforcement in the wall, since the wall is loaded in shear. The rim well and the spoke bed have 0° reinforcement layers in order to increase the bending stiffness of the rim. The wire in the bottom was known, but it is now clear how it is build up.
This test shows that the automatically produced rim needs reinforcements in the rim well and in the spoke bed. The side wall however can be made with ±45° only, which is beneficial to manufacturing a double bend rim out of continuous material.

4.1.3 Discussion

Not knowing the correct temperature risked the carbon fibres getting burned when the temperature is set too high or that they float away due to convection. In the end it was found to work at 400°C.

The carbon was examined in a bag, due to the risk of breathing in the fibres. However, working with carbon in a bag is not ideal and making pictures was hard through the bag. A camera with more megapixels and a better sensor would also have been preferable. An improved way to take the layers apart would have resulted in a higher certainty of the layup. An option could be to use a negative pressure chamber, similar to what is used when working with chemicals, such that the fibres pose no harm for the examiner. This would leave the examiner with more room to work and a more transparent workspace than a small plastic bag.

4.2 Test 2: Weave adaptability to strain

The second test was to find out at which widths a reinforcement of 0/90° weave would be constrained by circumference differences when the rim will be produced. The test's main goal is to see what the maximum width of a strip of 0/90° CFRTP is before it cannot conform to the rim without buckling the fabric. Weaves have an inherent "looseness" that can withstand strain differences up to a certain point. Three strips of different size and length were cut and used to place onto a mould. The centre of the fabric is laid on the mould and pushed down along both sides of the mould. This method tries to have no buckling in the centre of the fabric and to force the strain at the edges to be resolved by the looseness of the weave. Tape was used during cutting and placement to make sure the fabric would not unravel. The fabric is then held in place by tape to see what the effects of the circumference differences are. The exact process and the equipment needed for the test can be found in the appendix B.2.

Doing some basic calculations on the circumference differences shows that the strain on the material, when the 0/90° reinforcement is one centimetre high on the rim, is equal to:

Equation 2: Strain

$$\epsilon = \frac{\pi * \ d_1 - \pi * d_2}{\pi * d_2}$$

Using 633mm for the outer rim diameter, 50mm as the rim height and 10mm reinforcement height on the rim, the strain becomes:

Equation 3: Strain equation with rim values

$$\epsilon = \frac{534 - 533}{533} = \frac{1}{533} = 0.19$$

Therefor the strain per wheel is 0.19%, which has to be resolved by the looseness of the woven fabric.

4.2.1 Results

The first strip, 2cm width, conformed to shape well. However, there were wrinkles and buckling present, as can be seen in figure 32.

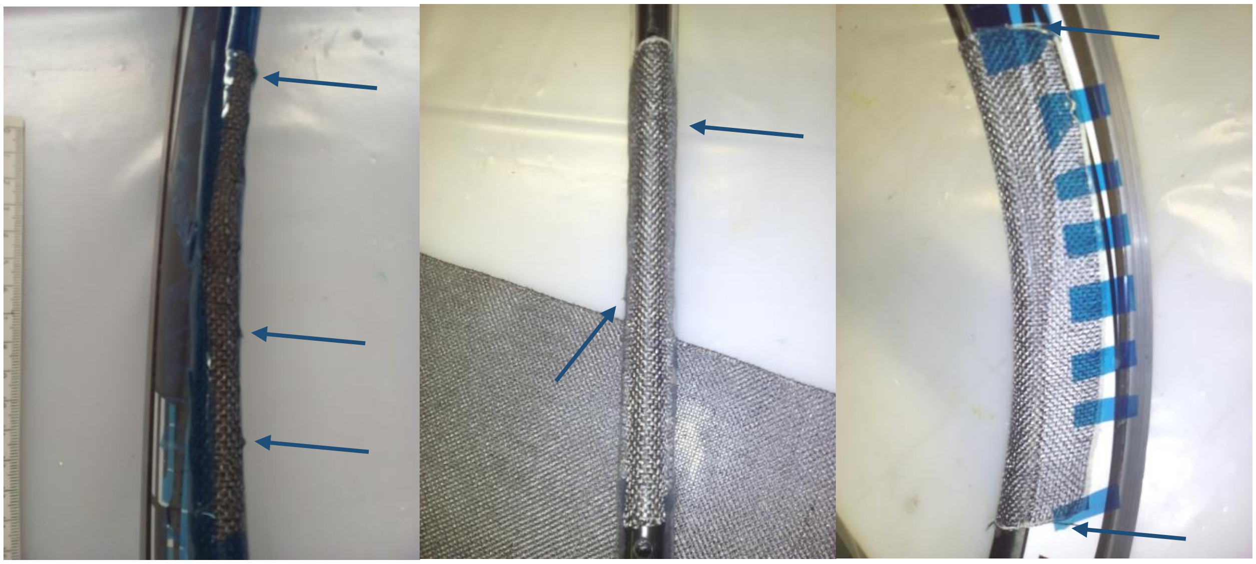


Figure 32: From left to right, 1: 2cm width with too much tape to hold it in place. Due to the inaccurate placement of the holding tape the weave has wrinkled. 2: 6.8cm from the top, some wrinkling on the top, but generally flat on the mould. 3: 6.8cm from the side. It is visible how the initially square piece of fabric now changes shape in order to cope with the strain differences. However, the tape used to deter unravelling of the fabric made the edges stiffer than the fabric in reality is.

Strip number two, with a width of 6.8cm, showed the strain problem well. Figure 32 shows how the edge of the strip does not seem to align with the inner part. The separated taping was less prone to keeping the weave from conforming to the double bend shape. However, the tape that was placed on the edges of the strip to deter the weave from unravelling did restrict the weaves' ability to conform to the double bend.

The third strip, with a width of 4cm, is the longest strip with 60cm length. It follows the rim's shape well, but wrinkles after some distance (as can be seen in figure 33). These wrinkles can be flattened using the looseness of the weave, resulting in a proper shape conformation.

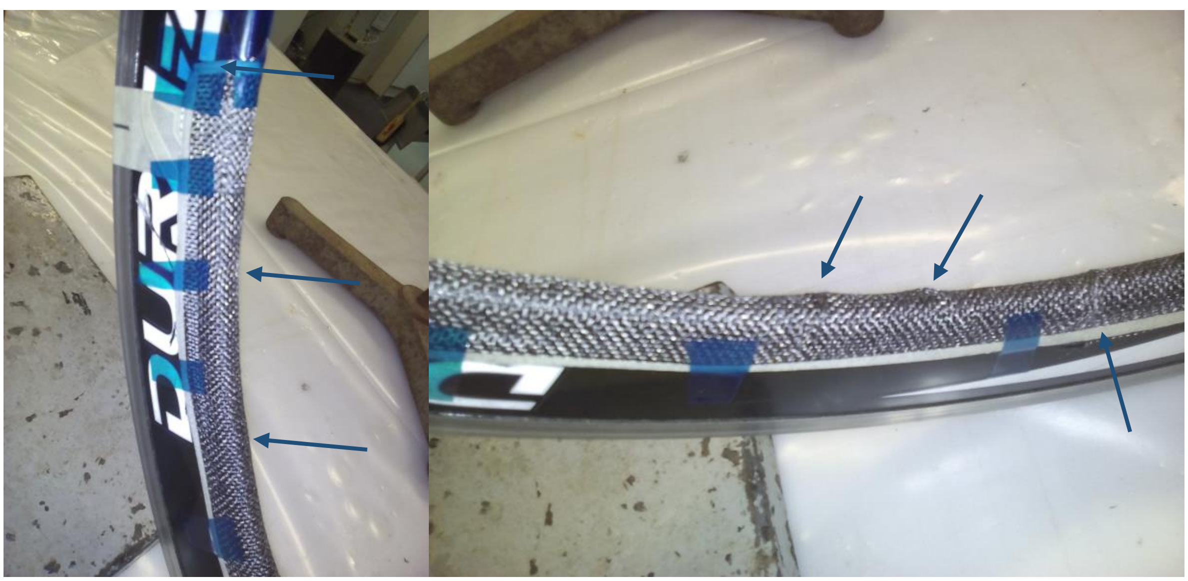


Figure 33: The wrinkling induced by the strain differences on the 4cm wide strip. The remaining tape on the carbon was to prevent the weave from unravelling after and during cutting, but resulted in being stiffer than the weave itself.

4.2.2 Conclusion

The test confirmed that a weave can shear in the ways necessary to endorse a forming process which involves 0/90° reinforced plastics, since the widths that are needed for the actual forming process are only between 1 and 10 millimetres. Most wrinkling and buckling that occurred in the weave was caused by mishandling and misplacing the material during the test, since little force was needed to make the fabric conform to the mould again. The 0/90° weave is only necessary to contribute to the bending strength, which is needed at the top and bottom of the rim cross-section to create the sufficient amount of second moment of area.

4.2.3 Discussion

It was noticed that handling loose fibre cloth, and with these widths, was difficult. Taping the strips to the mould was inaccurate in both positioning and orientation. The strip adhered to the shape really well and was easy to fold over the mould. The wrinkling and shearing that is seen are from handling the fibre, not because of the shaping.

The method that is used to apply the material to the mould should be more precise, such that the effects of the shape can be seen more accurately.
It can be seen that the lines stay well in contour for quite some distance, see figure 32. Though at the end of the strip one does clearly see some strain related issues when it comes to the length of the inner and outer edges of the strip.

The 4cm width by 60cm length strip was made to see how much of an influence the total length would be on the strips' ability to conform to the mould's shape. A strip of 4cm wide was chosen since the 6cm one had some strain related issues after 15cm length. The 60cm long strip was fairly hard to form into the shape due to the length and the improper way of attaching the material to the mould. It did show that trying to form a single piece of roughly one third the size of the wheel seemed to be very doable. Every so often a pocket of material was formed, which was easy to form away by stretching the material. The tape that was used to prevent the edges from unravelling was actually what made the weave stiffer and harder to deform than the material itself. This is because the tape prohibited the edges to shear.

More testing was not deemed necessary since this test gave enough feel for the fabric to be able to conform to the shape without having strain related issues.

4.3 Test 3: Thermoplastic sheet forming test

A double ply of thermoplastic 0/90° prepreg is used to test the formability when subjected to their processing temperature and shape adherence without a reflow process.
The PA12 carbon fibre composite sheet is created using the Joost press beforehand and cut into usable sheets. The sheets can be seen in figure 34 and process on how to make the PA12 sheets can be found in the appendix B.4. After the sheets are heated they are be pressed into the mould. The material is then allowed to cool down. The specimens are then taken out of the mould to see how well they keep their shape. Sheets with 2cm, 3cm and 5cm width and 20cm length are used to test what the implications of the width are for forming difficulty and to see what happens to 0/90° when double bend. The equipment and process for test 3 can be found in Appendix B.3. Since the strips are not that wide, it is expected to conform to the mould without issues. The thinness of the sheets could however result in easier buckling and increased speed of cooling down.

Figure 34: The three strips of thermoplastic tape, from left to right: 2cm, 3cm and 5cm wide.

4.3.1 Results

In the end there was no forming possible. The sheets come out of the oven at the set temperature, but as soon as the source of heat is taken away the sheets cool down too fast to form. Add to that that the mould is cold, this results in immediate stiffening of the material and in no forming. Later testing showed that the cooling rate of PA12 is around 5°C per second. Considering it took 5 to 10 seconds to bring the composite from the oven to the mould, it had already cooled down below the materials' forming temperature.

4.3.2 Conclusion

A different type of thermoplastic material should be used for testing. PA12 is not a simple material to work with due the high crystallinity (Narula, 2017). The temperature window at which the material is workable is too narrow.

4.3.3 Discussion

A better way of applying the sheet to the mould after or during heating is needed, such that the temperature of the sheet does not drop below the forming temperature of the material. Sandwiching the CF sheets in between metal sheets to contain the temperature during transit to the mould was tried, but even with the extra heated mass the temperature dropped below the processing temperature. Having a

way to constantly apply heat to the material during forming would be optimal, for instance a silicon blanket was suggested. Heated moulds would be very beneficial, since the fast cooling of the sheet hampers forming.
The T_g of the material is between 50°C and 85°C, but this is the low T_g and so it seems not high enough for forming. It was noted at a later point in time that a temperature between 160 and 170°C will be necessary for easy forming. The reasoning for this is the high crystallinity of the PA12 (Prithul, 2017).

No more further testing was attempted due to the difficulty of the material and the equipment needed in order to be able to shape the material into the mould. A setup with the oven right next to the mould, or heated moulds, or the mould inside an oven would be necessary.

4.4 Test 4: Minimum width of a braid under tension

This test is to see what the implications on the braid are when they are put under a constant tension force. Due to the nature of woven fabrics, the material can change the width and length depending on the fibre angles. A tensional force during production could give the process a better control over how the fibres are placed. The process and material needed can be found in the appendix B.5.

4.4.1 Results

The braids showed a 30% decrease in width from around 120mm to around 85mm (as can be seen in figure 35) and their respective fibre angles changed to around 30°instead of the base ±45°.

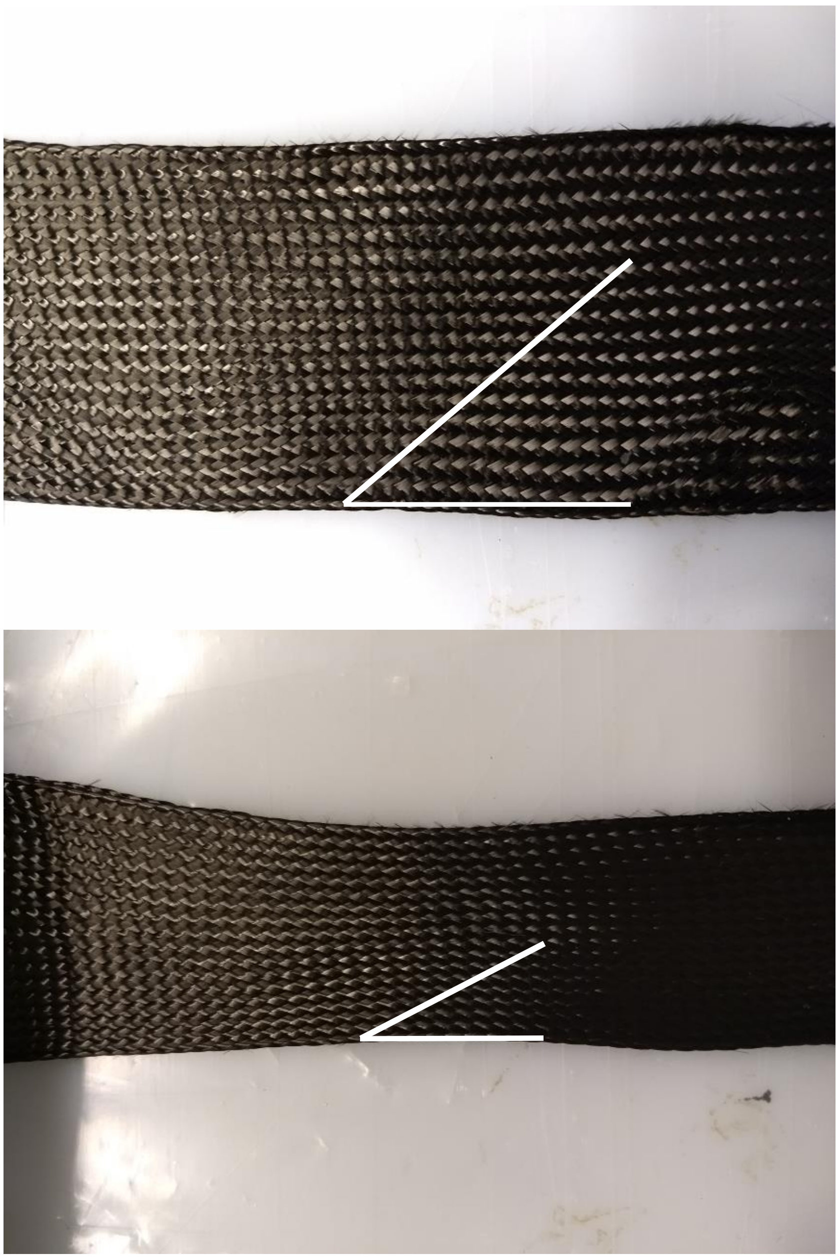


Figure 35: Top: Before, with a fibre angle of around 45 degrees. Bottom: After, with a fibre angle around 30 degrees. The apparent lengthening and the reduction in width due to the applied tensional force on the braid. The change in fibre angles is also clearly visible.

4.4.2 Conclusion

The carbon fibre braid responds well under tension and the property exhibited might be usable during production. It could be used by pre-tensioning the carbon braids while rolling or placing them in a mould, resulting in a more controlled and precise process. If the braids would be ordered such that the tensioned state is the width needed for the final product, the precision and quality of the fibre alignment could be improved greatly. Broadening of the fabric was not tested, since this would need compressive forces or transverse tensional forces. Since pushing the fabric is unfavourable due to the wrinkling and buckling of fabric based materials, broadening was not considered important to test.

4.5 Test 5: EUROCARBON braid with vacuum infusion

Test 5 is done using a 3k ±45° Braid from Eurocarbon. The goal is to see if a braid could be a feasible alternative for an automated process, since a braid can be made automatically and relatively cheap compared to pre-pregs. In the regular process, carbon fibre weaves or prepregs are cut and laid in the mould in sections. This cuts the continuous fibre and decreases the effectiveness of the structure depending on the level of discontinuity and the fibre overlap. A braid can automatically be placed in a mould and then be infused using RTM. Braids would allow for the rim to be made out of continuous carbon fibres, apart from the overlap, instead of prepreg sections. For this test however, vacuum infusion is used since it is relatively cheap and simple to do when not mass-producing and all equipment was readily available. The braid was flattened, creating a 4 ply sheet with rounded edges instead of cut edges that have the tendency to unravel. The diameter of the braid was smaller than what was needed to cover the mould when flattened and therefor had to be broadened during placement. After placement the entire mould was bagged and a vacuum was applied. Resin was prepared and the product was infused. Figure 36 shows the product just before infusion. More information on the needed equipment and the process can be found in appendix B.6.

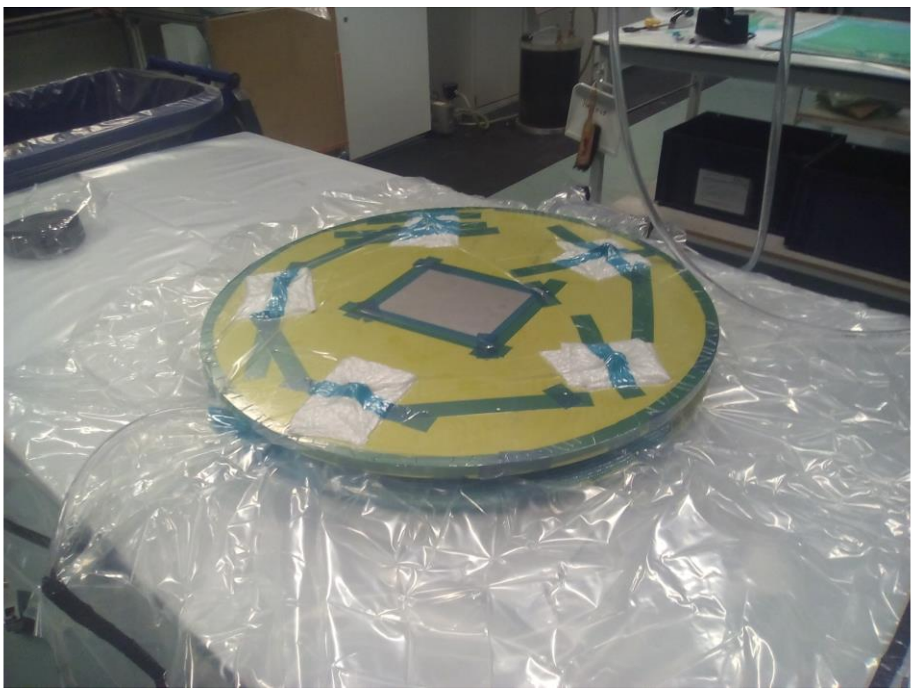


Figure 36: Setup of the product after placing the fibres in the mould, bagging the mould and applying the vacuum.

4.5.1 Results

Demoulding of the rim had some difficulties due to the resin getting into unexpected places, but remained unscathed. The mould itself received little to no damage after cleaning the excess resin. It was immediately clear that the product was not perfect, showing air pockets and voids. This can be seen in figure 37.

Figure 37: Left: Voids and pockets where the braid was pulled away from the mould and no resin was cured. Right: Voids in the top, the overlap is smooth apart from the fibres that were outside of the mould and at the bottom of the picture the fibre angle change can be seen as well as a wavy pattern where the braid flows from top to bottom of the rim. The braid follows the contours of the rim nicely.

The carbon did not have proper contact with the mould at all locations due to the manner in which it was fixed in place during the process of vacuum infusion. The fibres were wetted well, even though there were areas with resin pockets and air pockets. The rim felt stiff for an open cross section. The fibres of the weave cohere nicely to the shape, and any misalignment is due to handling during preparation for vacuum infusion.

There was a wavy pattern in the fibre due to the method used to fix the braid into place during manufacturing. The rim released from the mould well. There are some openings between fibre clusters due to the handling of the braid as well as due to the broadening of the braid. Shearing occurs from the inside rim towards the outside, where the angle of the fibres go from ±45° towards ±30°.

4.5.2 Conclusion

A braid is feasible to use and is automatable, one would have to come up with a process that does not utilize vacuum infusion. Vacuum infusion is very time intensive due to the curing time needed and labour intensive due to the needed vacuum bag. Therefore it is not considered an option for automation. ±45° can be used perfectly without alterations and without worrying about major shear deformations, however the shearing does cause the weave to go towards ±30° at the outer edges of the rim, which could have an effect on the structural properties of the rim. This phenomenon had also been shown by Ghalghachi (2016). A braid solves the problem of loose strands when forming and automatically gives two plies. The fact that the product is not perfect is not as much an issue, since it is still able to show the idea and how the fibres react to the shape.

4.5.3 Discussion

During the process of vacuum infusion there were factors that did not go as expected.

The braid that was used was 4cm in diameter. It was not easy to widen this braid to the necessary width, therefore it would be better in the future to use a wider braid from the start, where the flattened braid is equal to the circumference of the desired product.

Fixing the carbon fibre in place with tape was not precise, and it caused arching of the material in between the fixation points. It is advised to use some sort of adhesive in the future.

At first it was attempted to bag just the part of the mould where the rim was, this would have circumvented the problem of dealing with the sharp edges and the protruding bolts. It was however found that bagging the entire mould was faster and easier. In future production, it would be important to cover all holes, sharp objects or edges with a breather material.

During the first pull of vacuum for leak checks, it seemed as if there were minor leaks present. However, since a less optimal job was done with respect to ventilation of the mould and bag, there was a lot of trapped air inside the mould and bag with no ways to the exit tube. It took a long time for all this air to get pulled out.

The time the total process took was close to 8 hours instead of the 4 hours that were planned, with more experience it would become faster. However, it would probably still not be fast enough for mass-production, which would require a maximum of 3 hours of human labour per rim. (Doevendans, 2016).

Resin pockets and voids were prevalent, a different way of making the braid conform to the mould's shape is needed. Taping the too small braid to the mould resulted in the braid being lifted from the bottom and thus not making contact during infusion. A bladder could force the braid into the mould and make it conform to the shape better.

The resin got into places it was not supposed to flow to. For example: the bleeder fabric used to protect the vacuum bag from getting pierced by the bolts was filled with resin, there was resin in between the moulds, some holes for bolts were filled with resin and resin made its way up and over to the outside of the mould. A way has to be found to restrict the flow of resin to the areas where resin is wanted and nowhere else.

It is advised to coat the entire mould with release agent making it easier to clean and deconstruct after infusion.

4.6 Test 6: A broader EUROCARBON braid and a bladder

In test 5 the braid did not conform to the mould properly and the mould was not properly filled, thus it was decided to test a braid with a bigger diameter in combination with a bladder. The test is done using a 6k ±45° braids of 7cm diameter from Eurocarbon to see if a wider braid would be easier to form, follow the shape of the mould properly and have a proper finish to the product. The braid was placed into the mould after a slight broadening and being flattened. It was held into place with brackets. A second braid was pulled over a bladder tube and placed inside the previously placed folded braid. The entire mould was bagged and a vacuum was applied. For the exact process and needed equipment, see the appendix B.7. Figure 38 shows the finished bagged product.

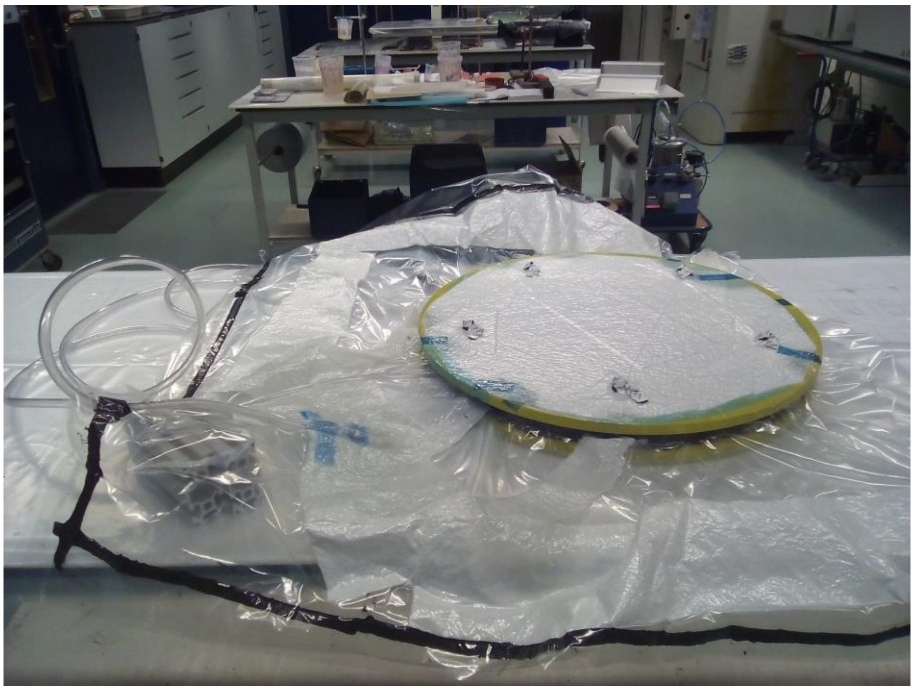


Figure 38: Product right before infusion. Enveloped in vacuum bag, with white breather material over the moulds as protection against leaks from sharp objects.

4.6.1 Results

About two hours after the start of infusion the entire mould seemed to have been wetted and the resin was reaching the exit tube. After 24h of curing the resin was not considered cured enough to be taken out of the mould, even though the curing time of the resin is 24h at room temperature according to the datasheet.

The morning of the third day, about 36h after infusion, the resin had cured. Taking apart the mould was much easier than in test 4, since this time the entire mould had been waxed. The part came out of the mould easily, except for the parts where breather fabric was pushed close or into the mould when creating the vacuum. The position where the bladder tube was going into the part has also turned into a rather big resin pocket.

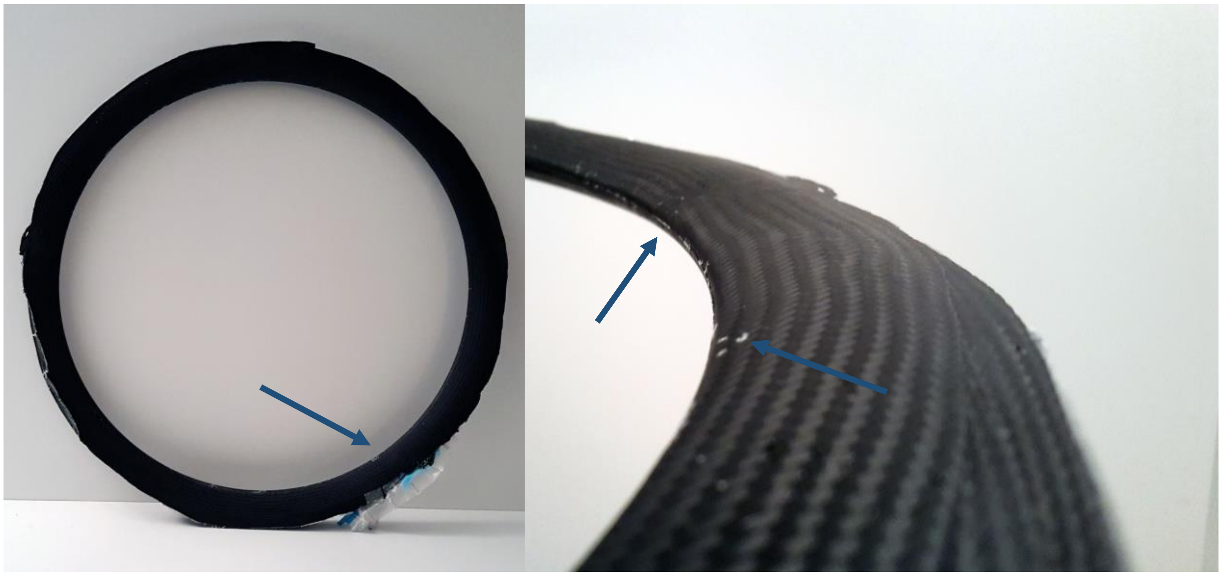


Figure 39: Left: finished product, with the remains of the bladder entry still visible in the bottom right. Right: The voids and irregularity of the fibres. The overall shape that is held by the singular braid and the fibre angles that move with the bend are promising.

There are some air bubbles present on the rim, as can be seen in figure 39, but overall the quality is good and the fabric followed the contours of the mould well. The hollow section is created nicely overall, but the top of the section is not even. Differences in how the bag closed during the creation of the vacuum caused the shape to alter. This can be seen in figure 40. Even with more cautious placement of the fabric, there are still places where the fibre alignment is not ideal. The fabric that covers the bladder has a very proper alignment.

Figure 40: View of the finished product and the closed cross section produced with a bladder. The "flow" of the braid follows the contours of the rim nicely, but there are still some misaligned fibres caused by handling during production.

4.6.2 Conclusion

Using a bladder system to improve the quality of the product worked very well. The broader braid provided more material and was able to conform to the mould.

4.6.3 Discussion

Lowering the pressure for curing resulted in immediate flow back into the mould. A lot more excess resin should have been present in the exit tube before trying to lower the pressure.
The ends of the bladder kept popping open, resulting in the implosion of the bladder when a vacuum was applied to the mould. During this test the bladder was not continuous, resulting in a large resin pocket at the point where both ends meet up. Having the breather material in the vacuum bag to assist ventilation helped much with getting a proper vacuum on the mould. A long exit tube was made in order for excess resin to have enough tube to flow in to. A part of the exit tube hung next to the vacuum pump. The vacuum pump heated the tube thus far that it became mouldable and it collapsed due to the vacuum. In this instance there was still a vacuum on the bag and the tube was long enough that the damaged part could be cut away and reconnected to the pump. It could have been that the pressure measured was not actually from the mould, but just the tube between the collapsed tube and the pump. This was noticed when infusion had already started and could have resulted in a total failure if the pressure had not been correct.

The proper shaping of the rim well was not part of this test, but a next step would be to make a rim with the proper design and shape now that it is shown that braids can follow the contours of the mould.

4.7 Test 7: Outer mould and Spoke bed reinforcement

Test 6 showed that a broader braid was beneficial to the quality of the product and a bladder helped shape the rim. Test 7 tries to implement these findings together with an outer mould and a spoke bed reinforcement, to see if a proper rim design including the rim well could be produced and with a better quality finish. Three braids were used in order to ease the production and have each component have its own reinforcement. The inner rim braid is flattened and laid into the mould first, in a roll form style pull under a small tensional force. Reinforcing UD fibres are pulled into the mould in the bottom of the first braid under tension, securing the braid into the bottom of the mould. Figure 41 shows the status after pulling in the reinforcing UD strips. A braid is pulled over the bladder like a sock and placed on top of the UD fibres, inside the inner rim braid. A last braid is flattened and placed on top of the braided bladder to close off. The mould is bagged, a vacuum is created and the product is infused. The used equipment and the exact process can be found in the appendix B.8.

Figure 41: The placement of the inner rim braid and UD stiffener strips.

4.7.1 Results

The test went in the wrong direction 10 seconds into the process of fusion. All the resin seeped through the nooks and crannies of the two moulds and filled up the breather material around it immediately, as can be seen in figure 42. After about 1 minute the 1.3kg of resin was all in the breather material.

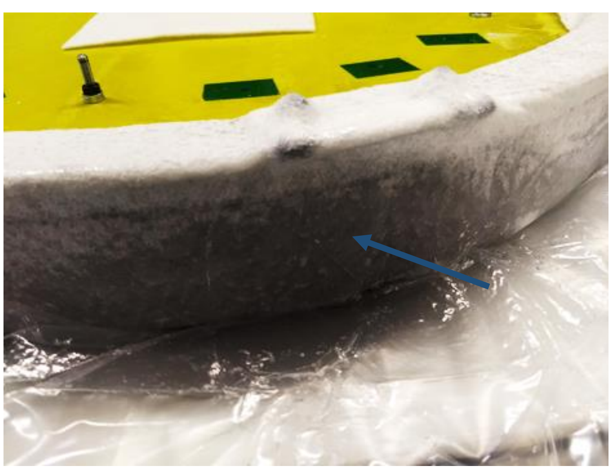


Figure 42: The resin leaked into the breather fabric through gaps between the outer mould and inner mould, and gaps in the outer mould itself.

The bladder managed to push the fibres into the outer and inner mould quite well. After taking apart the mould (see figure 43), the resin did seem to have infused the part well enough for it to be stiff and no dry fibres had been found on the part. There are open spots that are not filled completely with resin due to air, but the fibres are still wetted, as can be seen in figure 44. After sawing the rim in half it showed that the fibers inside the reinforcing wire at the bottom are not fully wetted with some dry spots and voids. Figure 44 shows these cut cross sections.

Figure 43: The fibres are fully wetted, but the product shows a lot of voids. The fibres follow the contour of the rim well.

Overnight all the resin that did make it to the part went to the bottom of the mould. The fibres aligned well with the mould. The shape of the wheel gutter and the flanges are not well shaped, as can be seen in figure 44.

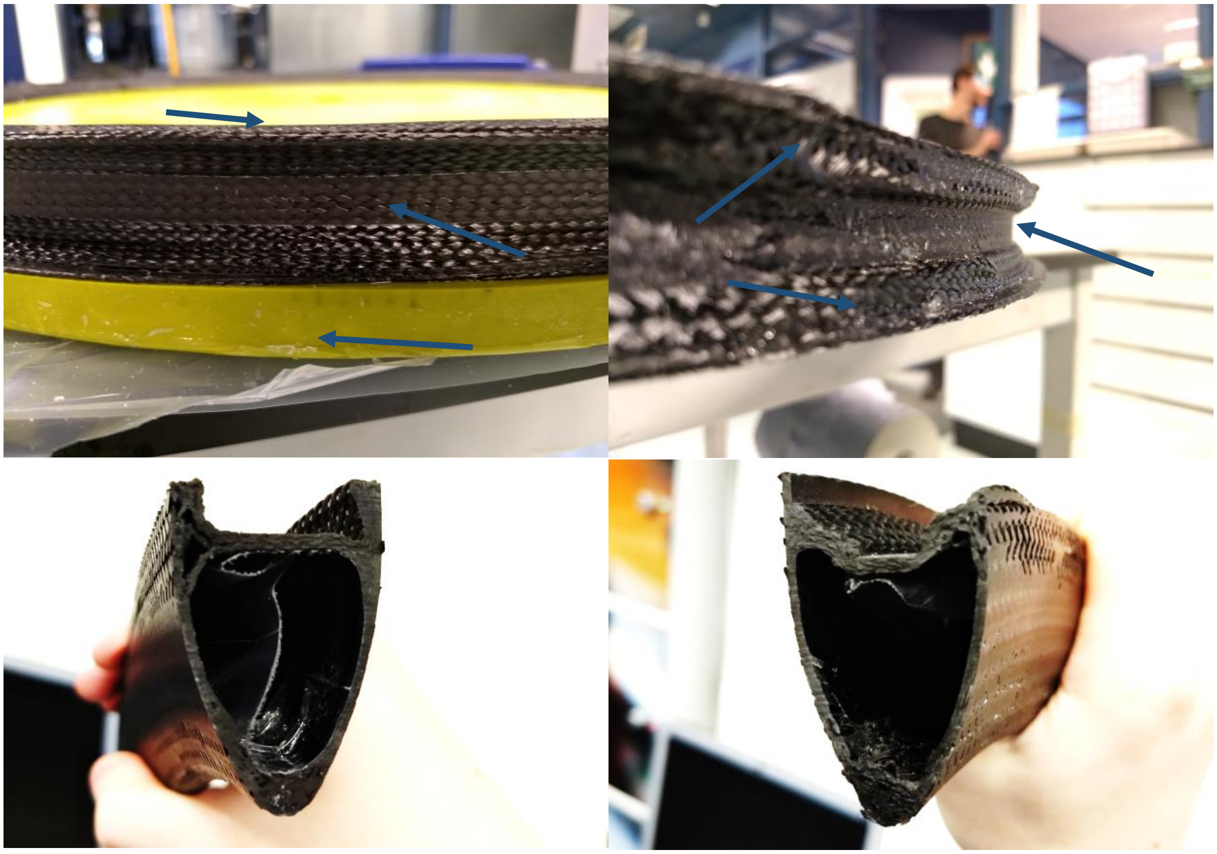


Figure 44: Top Left: Bladder pressed the gutter well against the outer mould. Top Right: Bladder did not press the rest of the material into the contours of the outer mould. Bottom Left: Voids in the corners of the hollow cross section and the reinforcing wire. B

4.7.2 Conclusion

The carbon braids were working well and as intended. It is expected from this that they fit well into any shape that is needed. The method can create parts with continuous fibres apart from the overlap and they make the production process very fast and look very neat. The brackets did their job well, they held the carbon in place locally while work was done elsewhere on the mould. This can also be seen in figure 45.

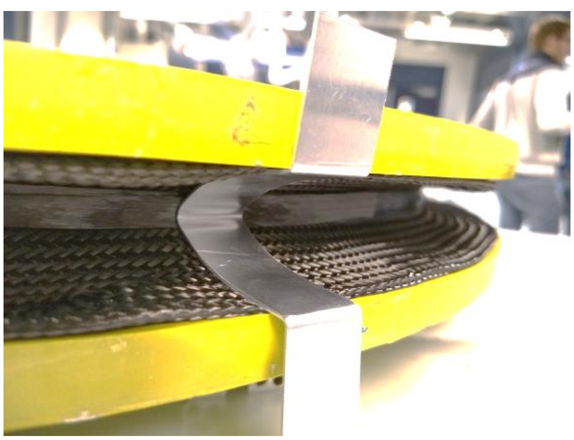


Figure 45: Outer braid of carbon fibre and the UD stiffener held in place by a bracket during production.

The two moulds do not fit together well enough, therefore resin could escape into the vacuum bag and surrounding breather material. The gaps can be clearly seen in figure 46 below.

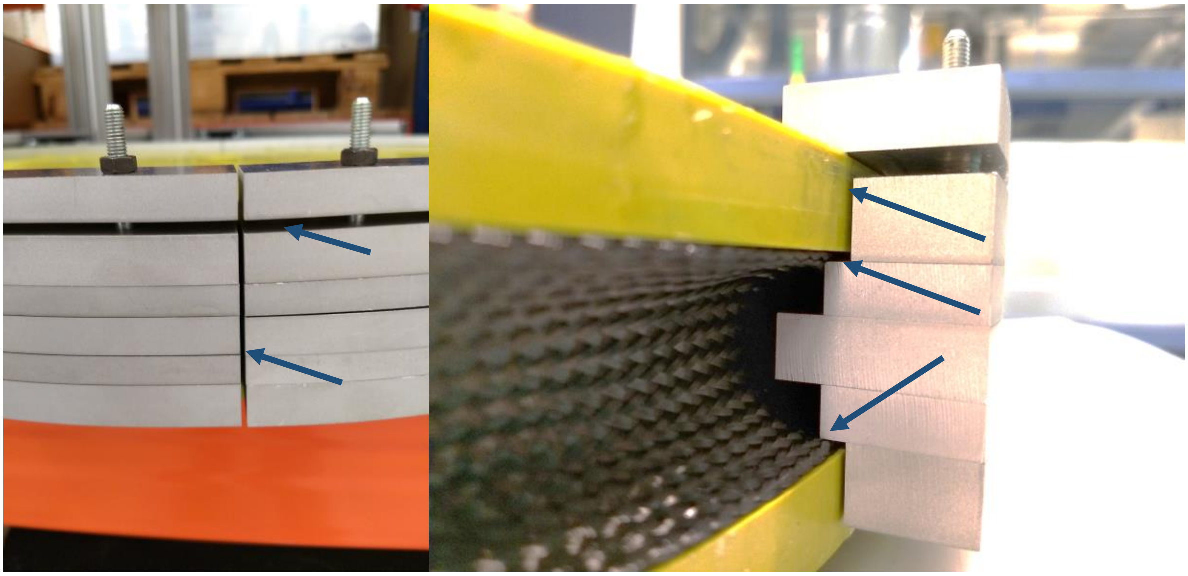


Figure 46: The gaps in between the two outer moulds that caused resin to be able to escape from the product and into the surrounding material. On the right at the bottom it can also be seen how the fibres are getting pushed inwards by the outer mould.

Using a bladder gave problems when trying to ensure no leakage of air. The bladder works well for the eventual shape, but gives too many problems at the same time as the methods used at this point in time are crude.

The flanges for the tire did not form well into the outer mould, this is due to the braids at the flanges getting pushed into the mould by the outer mould.

4.7.3 Discussion

A different solution might have to be found for the bladder, it was very hard to create an airtight seal. When testing the airtightness of the bladder, it also exploded once under the pressure, the result can be seen in figure 47. This resulted in having to unpack the entire mould and start over again.

The moulds in the end were not compatible, as can be seen in figure 46. It could be that using tacky tape around the inner mould and in between the outer moulds could have ensured that the resin did not flow into the breather material by filling the gaps.

Using a closed cell foam (Easycomposites, 2015) as an inner core material instead of the outer mould could reduce the production problems at hand and the need for expensive outer moulds. For a more detailed break down and possibilities, see the appendix C.

The carbon that is supposed to go into the area for the flanges of the rim well got pushed inward by the outer mould. The space is very small (as can be seen in figure 46), therefor manoeuvring the carbon into the correct position is difficult due to slippage and getting caught on the edges of the outer mould. A better designed outer mould is necessary in order for the flanges to have a higher quality.

Entrance and exit tubes for the resin need improved closure, so the resin does not flow out of the mould, see figure 47.

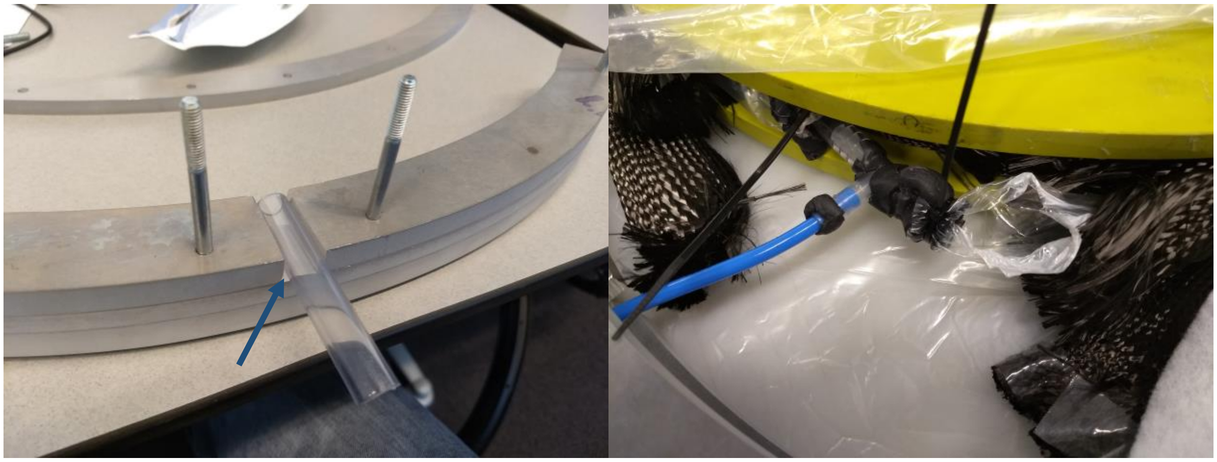


Figure 47: Left: Cut out in the outer mould for the inlet/outlet and the space between the tube and the mould. Right: Exploded bladder when testing the connections for leaks with overpressure.

4.8 Test 8: Altered outer mould and a new bladder type

Test 7 showed the potential of an outer mould, but also the problems that came with it. A second test with a slightly altered outer mould was done. A silicone bladder with only one open end was added as well, to ease the process of vacuum infusion. It is thought that changing the outer mould and the manufacturing process could change the outcome of the flanges. The outer mould is changed such that the vacuum bag pushes the outer mould into the main mould when under vacuum. The process of laying the braids into the mould is the same as for test 7, but the bladder is not inflated until the vacuum bag pushes the outer mould into the inner mould. The used equipment and the process can be found in the appendix B.9.

4.8.1 Results

During infusion it was known that the resin would flow to the wrong areas due to runners. Resin had flown into the breather material around the mould, this can be seen in figure 48. After around 15 minutes of infusion the resin supply was depleted and the infusion was cut off. The cured product resulted in a hard breather material infused with resin around the mould.

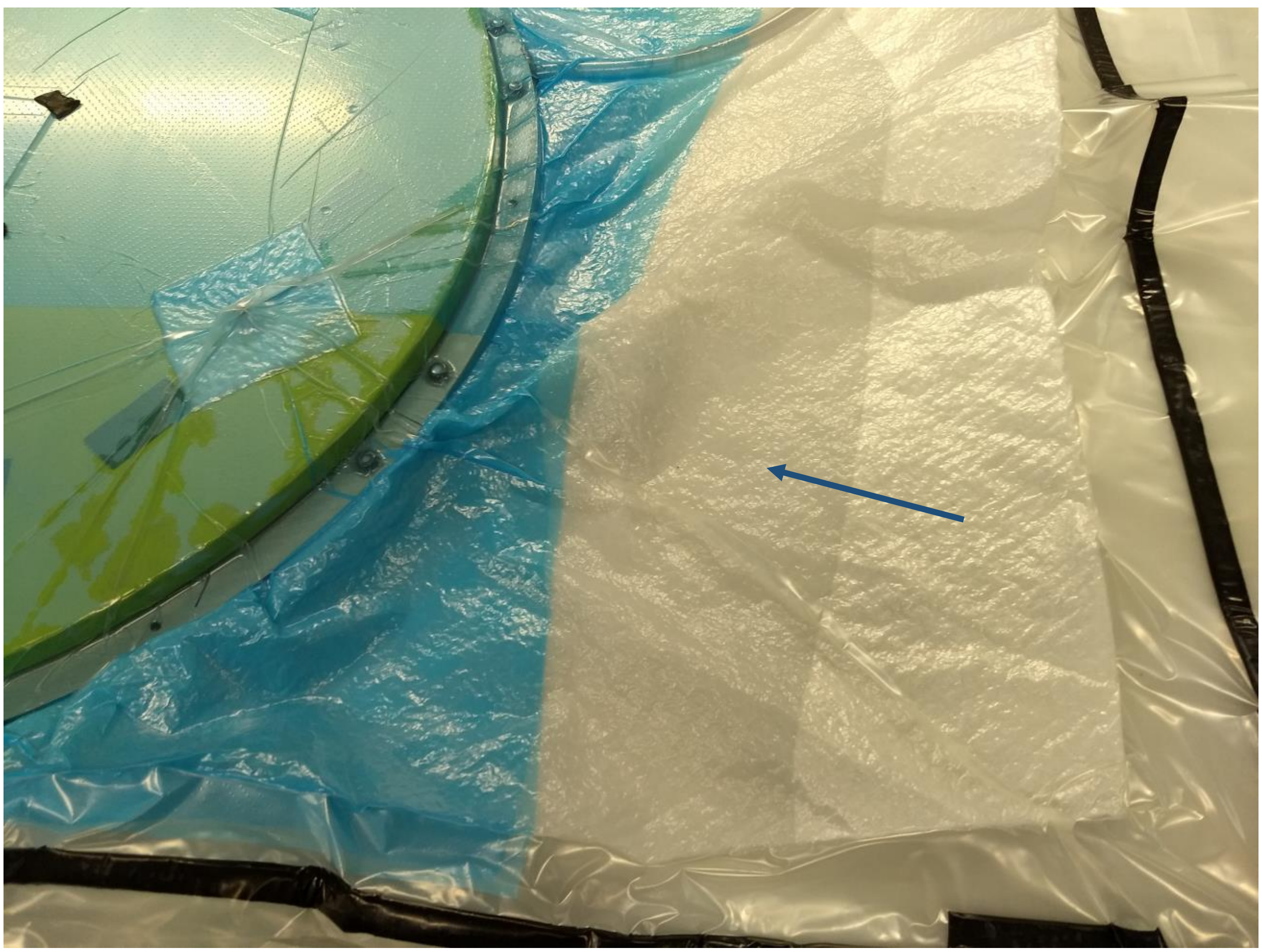


Figure 48: The outflow of resin from the mould into the breather fabric.

Unpacking the product was quick and easy due to the proper application of release agent on the moulds and the use of release film in between the breather material and the mould. There were big runners around the mould, where the vacuum bag was covering the flanges, this can be seen in figure 49.

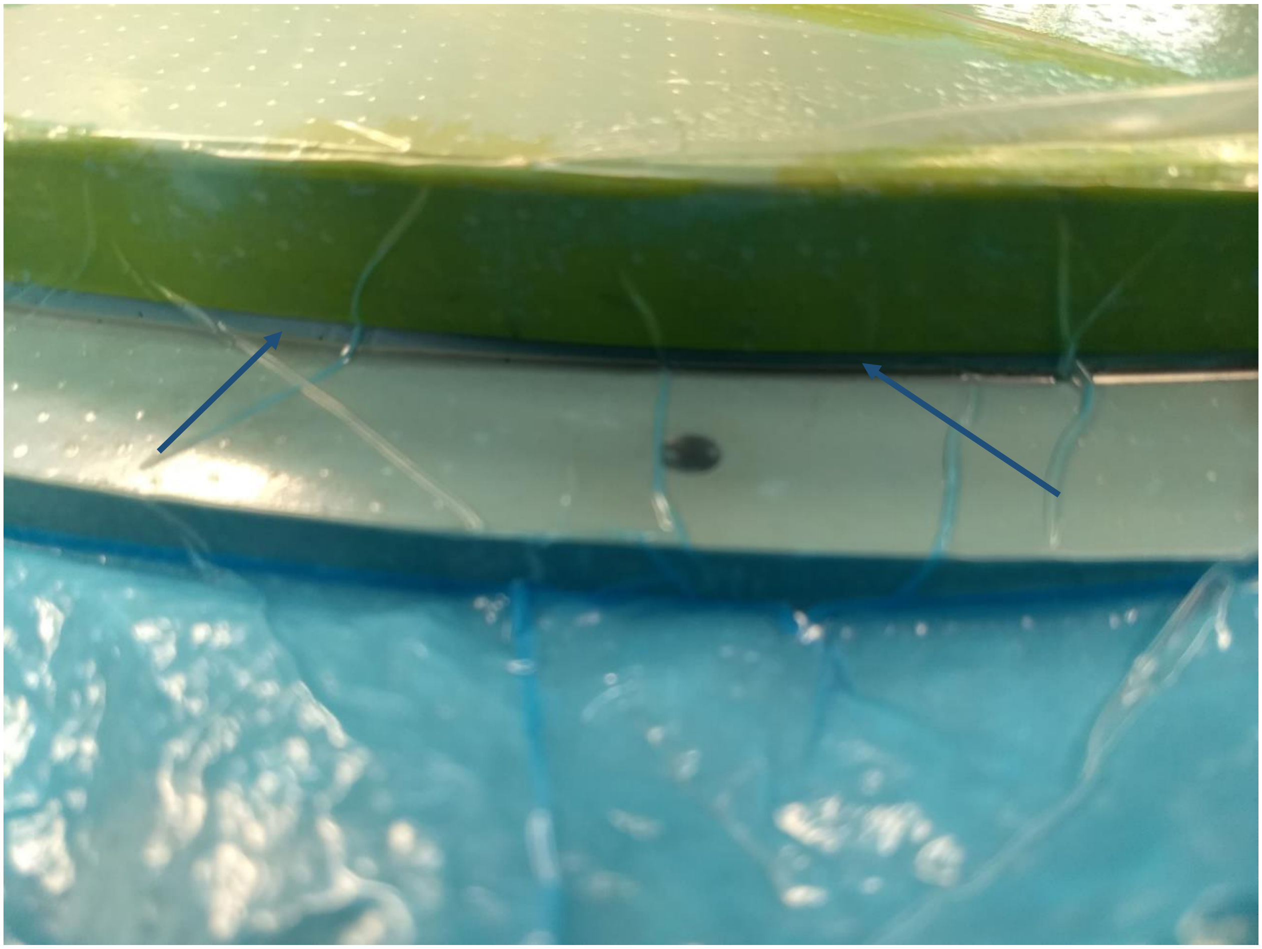


Figure 49: Runners between the vacuum bag and the mould.

Opening the mould showed the part, it had formed well into the inner mould for most parts and the fibres are aligned with the form direction. The main point of interest for this test were the flanges, the flanges exhibit many different states in this product and none of them were perfect. Most flanges are pushed inside the mould and outside of the flange area. Some flanges bulge outside of the mould and are folded over the edge, some examples can be seen in figure 50.

Figure 50: Flange imperfections. Left: Braid was pushed in by outer mould, resulting in no flange. Right: outer braid was pushed in with the inner braid extending outside of the moulds.

There are voids present in the product and there are several areas where not enough resin has been accumulated, as can be seen in figure 51. However, all fibres are wetted.

Figure 51: Voids and empty spots in the product

Another interesting point were the gutters. The bladder pressed the inner braid well against the outer mould, but did not manage to push the braids into the flange area. The braid did not conform to the outer mould shape as well as expected. In the areas where enough resin stayed after infusion, these pockets were filled with resin alone, in other areas it is clear that the braid did not adhere to the outer mould at all. This can be seen in figure 52.

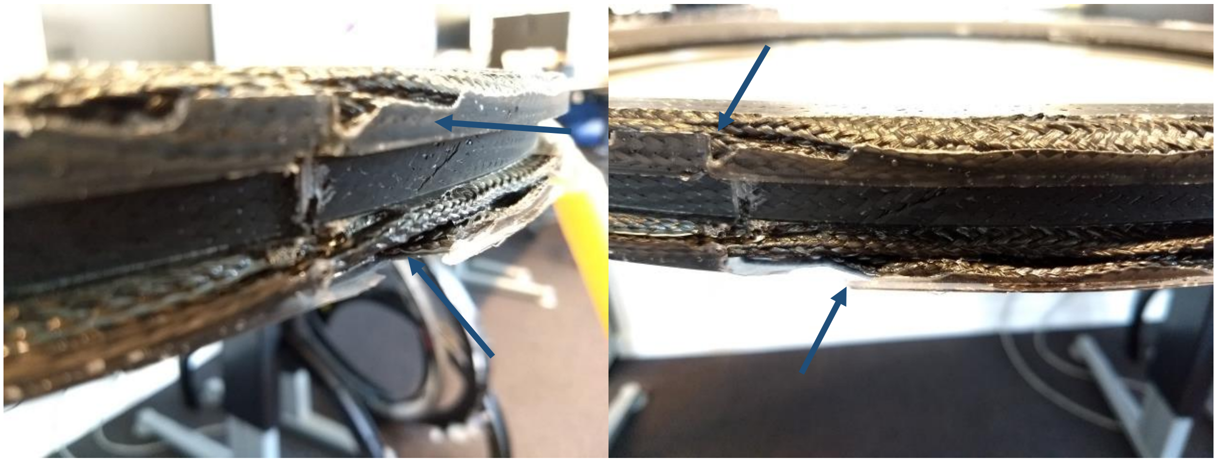


Figure 52: Rim well showing the non-filled walls and no confirmation to the shape.

4.8.2 Conclusion

Even with a method that was aimed more at getting a proper flange, it was still not possible with the current moulds and production method of choice. Braids were proven to be very viable for precise and automated production, but the moulds need to be properly manufactured for the material. The braids also tend to deviate from the position they are placed in when they come in contact with the moulds during manufacturing, but this would occur with UD layers as well if not more so. The braids get pushed inwards during the placement of the outer mould. This results in either no flange material, or just a singular braid infused as flange. The space between the inner and outer mould is also not sufficient to properly manufacture a flange of two braids thick.

4.8.3 Discussion

The bladder was an upgrade over previously used bladders. However, the bladder still does not have the ability to push the material in all corners due to bad design of the outer mould. The outer mould was designed based on cheapest and fastest availability to continue testing, a proper milled mould would cost too much at this stage. The bladder did give proper pressure against the inner mould and shaped the rim well. In the end the bladder also was not retrievable from the product.

In order for the bladder to exert as much pressure as possible on the moulds to produce the best shaped product, the infusion pressure was left at the minimum possible. The degassing of the resin was done near the same pressure as the infusion, which causes more voids and bubbles in the resin during curing and infusion. Normally infusion is done at 50 mbar and curing at 500 mbar which causes the molecular volume to be significantly smaller than at degassing pressure of 5 mbar, 100 times to be precise. Therefor the bubbles in the resin would be a 100 times smaller as well. Due to these tests being for shape and form mostly, the bubbles and voids were thought of as necessary trade-offs for the enhanced forming pressure.

Runners were a necessary evil in order to have improved control over the manufacturing of the flanges by being able to manipulate the carbon better. More thought should have been put in the possible flows of the resin. With proper care the product could have come out with less voids, but the flanges would still not have been perfect.

Even after experiencing the problem with the breather material in test 7, the same occurred in test 8. The breather material was in contact with the runners and that is why resin got sucked into it. After the resin in the bucket was finished, the excess vacuum in the bag in the areas of the breather material sucked resin from the product to fill the void. This caused voids and empty pockets in the product. Even though the breather material is necessary to protect the vacuum bag from the nuts, bolts and sharp edges of the mould, it should have not been in contact with any runners.

The release film was a welcome addition for the ease of opening the moulds and removing the vacuum bag. The release film also gave a little protection around the sharp edges of the outer mould.

Flanges are still an issue to produce controlled and with the proper quality. The flanges are pushed inside by the outer mould and probably a better mould design is needed to be able form them properly. The flanges are either too far on the inside of the mould or bulge outside of the mould. There are some parts where the flanges are as they are envisioned to be, but that is more an exception than the norm.

During forming the fibres were not always in the intended angle they were supposed to be due to handling of the fibres and the attaching of the outer mould pushing in the flanges. It is thought that if the braids are placed in the mould under tensional stress, the braids will keep their alignment.

There are areas that show the shape of the rim as the design intends it to be. However, most times this is resin that flowed into the open spaces and filled them following the moulds. It seems the design of the outer mould cannot be formed by a bladder and the braids. This is due to the fact that there are areas where the intended product only has carbon fibre and the bladder cannot apply any pressure there.

5. Conclusion

The main question for the thesis was if it was possible to automatically manufacture double bend shapes with carbon fibre reinforced material. The outcome of this is not conclusive, but gives answers to some of the questions that would help aiming towards total, or at least largely, automated systems. Braids show a very promising use for automation and can be used in conjunction with a matrix of choice, be it thermoset or thermoplastic. During the thesis the tests done were not proper with respect to the actual automation, but more towards shaping and forming possibilities of double bend shapes and highlighting critical steps in the proposed process. However, the material showed promise for automation. Thermoplastics were not tested well enough due to the initial focus in this thesis on forming and shaping issues that would lie ahead, but literature shows it as a very promising asset for automation. This is also a view shared by suppliers and manufacturers of thermoplastic composites. Roll forming shows promise as well, but will need better equipment and more testing in combination with thermoplastic composites to give a conclusive answer. Pre-formed thermoplastic composites have been found to be mass produced and used for production in the later stages of the project, but testing has not been conducted due to time constraints and equipment.

Roll forming has not been tested extensively, but the handling that was done during the thesis does show promising results when it came to the combination of braids and roll forming. The braids would respond well to being placed in the mould under tension. However, for proper testing to be done on roll forming, expensive moulds and stations are needed, since the moulds need to be milled and preferably heated as well.

Braids were used mostly during the project and have shown several useful traits that were noticed during testing. However, they also exhibit irregularities and insecurities when it came to manufacturing the way that was done during tests. It is thought that with proper moulds and methods these negatives can be controlled and the material can work well in automation. Braids conform to shapes and adjust to shape changes well, requiring little processing force. This is however a double edged sword, since it also requires little force/error to misalign the fibres. The edges of braids are also bend, since they are folded, this results in a clean edge if the placement of the material is done precisely and properly. Utilizing a placement under tension, the braids can be controlled precisely during production, but the fibre angle will skew away from ±45°.

For automation the use of a bladder does not seem to be a proper solution, several other solutions have been found in literature but have not been tested due to availability and scope of the thesis. It did however show that certain production materials and techniques could potentially give a proper automated product, if the process and implementation would be done sufficiently. Preferably when using a bladder the inner pressure needs to be 1 Bar or higher, which with vacuum infusion correlates with the fusion pressure. If the two can be separated, the amount of voids and pockets could be minimized by infusing at a higher pressure. A bladder results in a smooth finish on the product, but depending on the size of the bladder it can leave wrinkles when too large or pockets when too small. It is thought that an alternative method would be more useful in automation, such as hotmelt or wax cores that are melted and extracted after production.

Vacuum infusion is not a plausible way to automate production for a carbon fibre rim. Even though it was only used to test forming and shaping, this was made very clear during testing. The method is too time intensive and requires too many steps that are difficult to automate properly (for example ensuring that there are no leaks in the vacuum bag). The cycle time would be too high with too many man hours needed for a proper product. However, the method did prove that certain aspects of the production process are plausible for automation, if instead of vacuum infusion RTM would be used in conjunction with properly designed moulds. Each step would then still require human interaction, but it would become more controllable and predictable with respect to product quality.

6. Discussion and Recommendations

During the process of the thesis certain ideas and possibilities arose, but were out of scope. This includes problems with production, uncertainties and material deficiencies. In this chapter the recommendations for future research are assessed and explained. There are several separate components and areas in the process that are discussed, namely material, the mould and testing in general. The material section goes over everything regarding materials that have been used or thought of during the project, why they are or are not feasible for automation and what could be used in the future. The mould section goes over the difficulties with the mould and what can be done differently. The last section is about the testing and the project in general.

Braids have shown to be a really useful tool when it comes to shaping and forming a double bend shape. Braids are automatically manufactured to specification and are relatively cheap. However, braids result in thicker and heavier products due to the nature of the braid. A three braid solution was almost as heavy as an 8 layer pre-preg solution. This was measured by taking one of the manufactured wheels and weighing them, taking into consideration the production imperfections. Braids also influence the impact toughness and fracture toughness, which might lead to less plies needed. Future research on this topic is necessary to see if just three braids are enough for the requirements and the user experience of the finished wheel.

This project started out with the main goal of roll forming thermoplastic composites. PA12 was chosen as a material to work with since other students were already using it for their theses and there were not many readily available thermoplastic composites at that point in time. The material came in an already pre-impregnated weave. PA12 turned out to be a rather difficult material with very specific temperatures for forming. It would have been simpler to emulate the behaviour of a thermoplastic composite with less demanding thermoplastic matrices that are known not to have the inherent stiffness and strength needed for the final product. This way the experiments would have had a lower temperature and force requirement for forming and would show the possibilities of the forming process.

PE tape was seen later during the thesis. A company in the city of Lelystad in The Netherlands started manufacturing PE composites by means of pultrusion. The material has lower manufacturing costs and has very workable temperatures which are excellent for testing. The material properties would not be sufficient for a rim, but it can be used to show the forming and manufacturing process.

A thesis was conducted at the TU about the fusion of thermoplastic composites and its dependency on pressure, temperature and time. When done correctly, matrices can acquire engineering properties between 75% and 100% (Anbuchezhian, 2017). More testing has to be done on this to see if it would be a viable option to connect parts together. This could potentially lower the difficulty of the production process and improve the product quality. Parts could be separately made beforehand and joined together as if they had been manufactured at the same time. The implications of local heating and pressure on the surrounding area would need to be assessed.

During the thesis the moulds that were manufactured had shortcomings and they had their purpose changed over the course of the project. The main mould was designed with roll forming in mind. With a more proper design for vacuum infusion and with a smaller percentage of the wheel to be made, for example only a quarter of the wheel, the tests would have been easier to execute and less material would have been needed for each test. This way more tests could have been done with the material available and the entire process would have been easier to handle.

After some base testing, braids were found to be an alternative for the material used. An outer mould was then designed to further test the braids. The design was such that it was cheap to build, which in the end led to a couple of sub-optimal features. The plates that the mould was build out of were not 100% flat and tight on each other. This caused the resin to seep through. The four outer moulds also did not have a 0% tolerance during its manufacturing and therefor do not correctly fit around the base mould. This also caused the resin to flow out of bounds. This cheap and fast solution resulted in a mould that was very sharp around the edges, which is not a preferable condition when dealing with vacuum and vacuum bags. Sharp edges also result in runners due to the carbon fibre fabric not being able to conform to the 90°sharp angles. If the edges would be rounded to a 1 or 2 millimeter radius the results could be improved.

Testing should have been done on smaller sections to make the testing process more manageable and less prone to mistakes by the tester. The results can then be extrapolated to the whole rim. After proving that the method can provide a proper part of a rim the process can be tried on a large mould that would have the improvements that were found during the testing on smaller scale. Future testing should involve more tests based on a matrix and weave combination. All tests now have been done on thermoset resin with braids, just to see if the fibres would conform to the intended shape without cutting.

Vacuum infusion is a cheap way for initial testing that does not require a lot of expensive equipment or moulds. The means for vacuum infusion were readily available and forming tests were therefor done using this method. The process however is time consuming and prone to faults, which is not preferable when it comes to production.

For future testing a combination of the outer and inner moulds specifically for RTM or Vacuum Infusion should be designed. For cost reduction and simplification of manufacturing only opting for a quarter of a rim is a future possibility. Vacuum bagging, preparing the moulds and doing the infusion would also take significantly less time. The results can be linearly extrapolated to the whole rim.
At this point in time most testing that has been conducted was done purely for shaping and forming, to see if braids would be a viable option over sheets or weaves. The layup used has not been calculated nor FEM'ed. The layup was made to test the separate parts of the rim and see if braids could replace sheets and weaves for the ease of manufacturing that braids bring. Braids generally have better delamination properties due to not being parallel to other layers and in straight lines everywhere in the layer itself. Maybe when using braids, less layers are needed by default due to increased fracture toughness and delamination properties.
No testing has been done with respect to the layup that is necessary to achieve the strength and stiffness that is demanded by the cycling authorities. It is thought that current wheels follow standard carbon fibre protocol with balanced and symmetric layups. More testing should be done with respect to the layup to see if there could be any weight savings by needing less layups, or if the braids are not sufficient in their engineering properties to be used for cycling rims in the first place.

In this project, roll forming has not been delved into enough when it comes to the actual roll forming. The shaping and the limitations of shaping with fabrics are known and have been tested for braids to see that they indeed can be used for roll forming without many issues. For future research it would be useful to use materials that are less demanding on their processing temperatures and forces. This way the possibilities can be examined when it comes to thermoplastic matrices.

Getting the proper moulds and materials seemed to become quite expensive, and more thought should have been put into cutting the project into smaller, more manageable pieces that could be individually tested and super imposed. Thermoplastic composites are not a common material that is mass produced at this time. Therefor other more reasonable and comparable materials should have been used that exhibit the same properties, but have more lenient testing circumstances.

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Appendix

A: Literature review detailed information

A.1 Thermoplastic and Thermoset information

Thermoplastic matrices are made of plastics that are not cross-linked after curing. There are two types of thermoplastic, amorphous and semi-crystalline. Semi-crystalline exhibits both a melting point, T_m, and a glass transition point, T_g. Amorphous only has a T_g. (Mallick, 2007)
The glass transition temperature gives them the property that after heating them beyond this point they become more mouldable with temperature and can be reshaped. Depending on the composition of the polymer the needed temperature for forming could be at T_g or higher. This is due to the fact that the T_g is not a fixed point for the polymer, but more a temperature range in which the stiffness of the polymer goes down. Cooling them after shaping them makes them remain in their new shape. Thermoplastics of both kinds however exhibit lower mechanical properties compared to thermosets due to having less cross linking and being dependent on less strong secondary bonds. (Mallick, 2007)

The processing temperature for thermoplastics is higher than the curing temperatures that are necessary for thermosets. This has to be taken into account during processing and production.

Table 1 shows some of these typical service and glass transition temperatures for thermoplastics.

Table 1: Typical Thermoplastic matrices and their temperature properties. The T_g is taken as the point where the polymer first starts inhibiting lower stiffness, which does not necessarily correspond to the forming temperature. The maximum service temperature is defined as the temperature that the material can withstand for longer periods of time before impacting the engineering properties such that it is not structurally sound. (Mallick 2007; Lange+Ritter, 2017)

Thermoplastic matrix	T_g [°C]	Maximum service temperature [°C]
Polyether ether ketone (PEEK)	143	250
Polyphenylene Sulphide (PPS)	85	240
Polysulfone	185	160
Polyetherimide (PEI)	217	267
Polyamide-imide (PAI)	280	230
K-III polyimide	250	225
LARC-TPI polyimide	265	300
PolyAmide 12 (PA12)	85	170

When it comes to processing the thermoplastic composite during manufacturing, heating of the product is very important. The higher the temperature, the faster it cools down as soon as the heat source is taken away. The idea is to form the shape by only increasing the polymer to the processing temperature, which makes it formable. After it has been pressed and rolled into the shape that is wanted, a curing cycle could be applied afterwards to ensure the material from having internal shear or strain problems related to the deforming of the plastic. Temperatures at T_m will make the matrix reflow and reset, making the wheel sounder without residual stresses. An observation that has been made is that the material that will be used for most testing, PA12, cools down with a rate of around 5°C per second after heating it to T_m and taking the heat source away. (Anbuchezhian and Narula, 2017)

Thermoset pre-pregs have to be kept in refridgerators to ensure that the uncured resin is in a more viscous state and does not cure. Pre-preg carbon fibre sheets also have a limited shelf live, which means that after a while the products will not have the required quality.

A.2 Hollow cross section

This section shows more information on possible core materials.

A.2.1 Removable cores

A wax shape is put in the mould to which the carbon fibre can press against during manufacturing and curing. This wax mould ensures the inner shape of the cross section and after curing is heated and extracted when melted. A wax with a positive thermal coefficient of expansion is preferred, that way the wax expands with heat. When the wax expands it will provide a forming pressure from the inside, which is beneficent for the process.

There is also a company that sells Aqua Mandrell, a water soluble material that can be used to create hollow sections in parts. The mandrel can then be washed out with water after manufacturing. (Aero Consultants, 2014)

A.2.2 Bladder

A bladder is a hollow tube/shape that is able to apply pressure from the inside of the mould during manufacturing. The bladder has to have a positive pressure in order for it to be able to pressurize and keep the hollow section that has to be manufactured from collapsing.

A.2.3 Foam core

Foam core gives ease of manufacturing, but increase the total weight of the product without adding much extra strength. There is also the problem that resin can be deposited in the foam, making it heavier but not necessarily stronger. One would have to design around the fact that foam cores are used during the production process.

Polystyreen foam cores could be used , they can be shaped by and bought from manufacturers. Polystyreen foam cores can be taken out of the mould after forming by using acetone to dissolve the core and clean it out with water. However, the acetone needs proper contact and time with the polystyreen before it is able to dissolve. This way there will be no weight detriment. The removal of polystereen requires adequate facilities, which are also regulated due to the use of chemicals. (De La Roy, 2017)

A.3 Bonding information

Fusion bonding has the capability to exhibit the same quality as autoclave consolidated parts. This shows that certain methods can be used to decrease the difficulty in manufacturing. The parts can be formed seperately and joined later, but without compromising structural integrity, opening up different designs for the parts (Yousefpour et al., 2004). It has been found that fusion of thermoplastic composites requires a high amount of pressure, time and heat to ensure that the two matrices that are joined become one. As an example, for PA12 these values were found to be a temperature of 235°C, for 15 minutes under 10 bar of pressure. After these 15 minutes the parts perform and look identical as it would co-cured from the beginning. (Anbuchezhian and Narula, 2017)

Another way of connecting multiple thermoplastic parts is by welding them together. This means that multiple options exist; thermal welding, electromagnetic welding and friction welding. Thermal, hot plate and infrared welding techniques are suitable for both curved and flat surfaces, as it also delivers good quality parts. A downside is that one has to be careful of delamination and warping during the heating process. Electromagnetic welding quality depends strongly on the design of the used coil and implant configuration. High frequency friction welding is very suitable for complex structures, but these types of welding are not suitable for conductive structures since it will heat up the entire component. (Yousefpour et al., 2004)

Adhesive bonding is simple and is very automatable, but the application of the bonding agent is not properly certifiable. An adhesive bond requires a clean surface, enough effective surface area for the shear forces to be properly distributed and proper load paths such that peel stresses do not occur. During production the areas can get dirty or air can be trapped between the two surfaces reducing the adhesive effective area. The strength of the bond is not well known untill the bond is tested to destruction. Adhesive bonds are also not simple to repair, since the bond cannot be taken apart without breaking the adhesive and sometimes the surrounding material. This is an unfavourable aspect for most products that undergo maintenance. Adhesive bonding is mostly used in secondary structures that do not carry the main loads in a structure and therefore are not critical. (Crane and Dillingham, 2018)

B: Test Materials, Equipment and Processes

B.1 Test 1: Materials, Equipment and Process

Materials and equipment:

- An oven capable of 400C.
- Cross section of to be tested wheel (for this test it was t700 carbon with unknown resin).
- Tweezers.
- Ceramic crucibles.
- Plastic bag.
- Breathing mask.

Process:

In order to know the layup of the original wheel, a cross section of the wheel is cut up into sections that are flat and burned in an oven. The oven was set to 350 degrees at the start, but that did not result in enough burned away resin after 30 minutes. The oven was set to 400 degrees after 30min and after another 30min at 400 degrees the resin did burn away, but not entirely. The material felt more brittle

when touched with pliers. The crucibles were left to cool for 30 minutes before starting the procedure of investigating the lay up.
A pair of pointy pliers were used to peel away layers to see what was underneath, inside a plastic bag to ensure no floating of carbon particles and the hazard of breathing them in.

B.2 Test 2: Materials, Equipment and Process

Materials and equipment:

- Test mould (an old rim was used here).
- Different widths of 0/90 weave carbon fibre (2cm, 4cm and 6,8cm).
- Tape, preferably stretchable.

Process:
The process was the same for each strip of carbon fibre 0/90 weave. Subsequently however, small differences were made based on the experience on the first strip.

- Tape the edges where the weave is going to be cut with painters tape to avoid unraveling of the fabric.
- Cut the strips of carbon from the weave.
- Tape one end of the strip to the rim.
- Following the rim, press the weave onto the rim while trying to follow the rim shape.
- Every couple centimetres, tape the weave to the rim when it has conformed to the rim properly.
- Tape the last end when whole strip is on the rim.

B.3 Test 3: Materials, Equipment and Process

Materials and equipment:

- TP sheets (2cm, 3cm, 5cm).
- Mould.
- Rolling or moulding appliances (For this test brackets were made, see figure 53).
- Oven.

Figure 53: Left: The setup that was used, without the mould yet attached. The brackets and used thermoplastic composite in front. Right: Close up of the hand-made tin brackets.

Process:

- Heat in oven for 30 minutes at 140C.
- Take TP out of the oven.
- Hold TP over the mould and guide it in using the brackets.
- When the TP sheet starts to bend under its own weight, put it in the mould and press it down into the mould with a bracket.
- Continue this process down the sheet.
- Let the sheet cool down while held down by the brackets.
- Take out of the mould.

B.4 Manufacturing a PA12 carbon fibre composite sheet

Materials and equipment:

- Press with temperature control.
- PA12 composite tape.
- Isopropyl.
- Marble coating.
- Aluminium sheets the size of your product.
- Release film double the size of your product.

Process:

- Clean the press and recoat with marble coating.
- Clean the plates and coat both sides with marble coating.
- Package in the release film (make sure you take release film that can handle the temperature you are using).
- Set the program:

  - Apply pressure: 10 bar.
  - Heat up to 235C with 6C/min.
  - Keep it at this temperature and pressure for 15 minutes.
  - Cool down with 15C/min.
- After the cycle is finished, take out your product.
- Clean the press.
- Marble coat the press.

B.5 Test 4: Materials, Equipment and Process

Materials and equipment:

- Eurocarbon 6k 144/12 braid6.

Process:

- Reset the fabric to ±45 degree fibre angles.
- Measure the width and length.
- Put tension on the braid until it will not elongate any further.
- Measure width and length again.

B.6 Test 5: Materials, Equipment and Process

Materials and equipment:

- 1.3kg of resin (100:30 ratio of resin/hardener) Epikote 04908.
- Release agent (wax).
- Isopropanol alchohol.
- 5 m5 7cm+ nuts and bolts.
- Flow mesh.
- Breather material.
- Vacuum bag in which entire mould can fit.
- Tacky tape.
- Tube.
- Clamps.
- Vacuum pump.
- 4cm diameter carbon fibre 3k ±45 braid.

Process:

- The mould is cleaned on all surfaces.
- Wax is put on the surfaces that are going to be in contact with resin.
- The two parts of the mould are attached to each other with the nuts and bolts.
- The carbon fibre braid is cut to 2m, and the width of the braid is tried to be broadened.
- The broadening shortened the braid, thus a second piece of braid was cut and laid over the gap that was left.

- Place the carbon fibre in the mould, ensure the carbon fibre stays in the desired position using tape.
- When the carbon fibre is as desired, lay perforated release film over the carbon fibre.
- The exit and entrance of the infusion tubes are decided to be across from each other, the resin can then flow evenly from the entrance to the exit along both sides of the mould.
- After the release film, overlay the release film with flow mesh to ensure that the resin can flow to all locations of the part. End the flow mash around 10cm on both sides of the position of the exit tube to ensure that the resin has sufficient time to not just wet the whole rim, but can also penetrate into the depth of the part.
- In order for the entire rim to be filled with resin, take flow mesh and guide it to the edge of the vacuum back to the exit tube. If the exit tube would be near the rim and filled too soon, one side of the mould might not get wetted totally.
- Protect the holes, bolts and edges on the mould with tape and breather material to ensure that the vacuum bag does not tear.
- Apply tacky tape on the edges of the vacuum bag and close the bag. Put extra tacky tape around the tube so there is less likely to be a gap or leak around the tube.
- Ensure that the exit tube will not be closed due to pressure.
- Connect to the vacuum pump and check for leaks.
- Guide the bag the way you want it while slowly pulling a vacuum, see if the fibres and all layers are positioned as you want them to be.
- Mix resin, 1.3kg, 100:30. 1000mg of resin, 300mg of hardener.
- Degas resin for 30min with a sponge of scotchbrite to give the gas a nucleation site.
- During 30min, keep testing if vacuum bag is still whole and if all air has exited the mould and bag
- After degassing put the bucket with resin in a bucket of water, to ensure that the resin does not over heat.
- Throw exit tube over a high thing, this way there is a smaller chance the resin will end up in your pump, also make sure there is a bucket in the resin catcher of the pump setup
- Infuse at 50 millibar, this is to have smaller bubbles in your resin, since degassing is done at 10 millibar or below.
- After the entire product is visibly wetted, cut of the resin and let the pump on overnight at 500mBar.
- When the resin is hard, take away the pump.
- Let part cure for at least 24h total, as is stated by the resin data sheet.
- Take the part out of the mould.

B.7 Test 6: Materials, Equipment and Process

Materials and equipment:

- 1.3kg of resin (100:30 ratio of resin/hardener) Epikote 04908.
- Release agent (wax).
- Isopropanol alcohol.

- 5 m5 7cm+ nuts and bolts.
- Flow mesh.
- Breather material.
- Vacuum bag in which entire mould can fit.
- Vacuum tube to use as a bladder.
- Tacky tape.
- Tube.
- Clamps.
- Vacuum pump.
- 4cm diameter carbon fibre 3k ±45 braid for over the bladder.
- 7cm diameter carbon fibre 3k±45 braid to use as inner rim.
- Tin brackets with the cross sectional shape of the mould to form the carbon.

Process:

- The mould is cleaned on all surfaces.
- Wax is put on the surfaces that are going to be in contact with resin, so all surfaces.
- The two parts of the mould are attached to each other with the nuts and bolts
- The carbon fibre braid is cut to 2m, and the width of the braid is tried to be broadened.
- The bladder is cut to 2m, one end is closed with tacky tape. The other end has a tube inserted for pressure control during infusion.
- Lay the carbon fibre in the mould, ensure the carbon fibre stays in the desired position using the tin brackets, and do not apply too much force to keep fibre alignment as proper as possible.
- Pull the smaller diameter braid over the bladder.
- Place the bladder/braid combo in the mould, inflate the bladder afterwards to see if it is placed properly.
- The exit and entrance of the infusion tubes are decided to be across from each other, the resin can then flow evenly from the entrance to the exit along both sides of the mould. The exit tube for the bladder is next to the exit tube for the resin.
- In order for the entire rim to be filled with resin, take bleeder material and guide it to the edge of the vacuum back to the exit tube. If the exit tube would be near the rim and filled too soon, one side of the mould might not get wetted totally.
- Protect the holes, bolts and edges on the mould with tape and breather material to ensure that the vacuum bag does not tear.
- Put breather material around the mould in the empty parts of the vacuum bag in order to ensure the trapped air can be sucked out to create the vacuum.
- The entrance tube ends close to the edge of the vacuum bag, use flowmesh to create a way for the resin to get to the carbon fibre in the mould.
- The exit tube also ends close to the edge of the vacuum bag, use breather material to create a path to the mould. This way, as long as the resin does not reach the exit tube, the mould will be under vacuum and resin will be pulled through the material. Having the exit tube as far from the mould as possible gives the resin more time to flow through all of the material and reduces the chance for dry spots.

- Apply tacky tape on the edges of the vacuum bag and close the bag. Put extra tacky tape around the tube so there is less likely to be a gap or leak around the tube.
- Ensure that the exit tube will not be closed due to pressure.
- Connect to the vacuum pump and check for leaks.
- Guide the bag such that the bags connect in the middle of the mould while slowly pulling a vacuum, see if the fibres and all layers are positioned as desired. This way the bladder has the most even shape resulting in a nicer rim.
- Mix resin, 1.3kg, 100:30. 1000mg of resin, 300mg of hardener.
- Degas resin for 30min with a sponge of scotchbrite to give a nucleation site.
- During 30min, keep testing if vacuum bag is still whole and if all air has exited the mould and bag
- After degassing put the bucket with resin in a bucket of water, to ensure that the resin does not over heat.
- Place the exit tube over a high standard, this way there is a smaller chance the resin will end up in the pump, also make sure there is a bucket in the resin catcher of the pump setup.
- Infuse at 50 millibar, this is to have smaller bubbles in the resin, since degassing is done at 10 millibar or below.
- After the entire product is visibly wetted and there is enough excess resin in the exit tube to account for backflow, cut of the resin and let the pump on overnight at 500mBar.
- When the resin is hard, take away the pump.
- Let part cure for at least 24h total, as is stated in the resin data sheet.
- Take the part out of the mould.

B.8 Test 7: Materials, Equipment and Process

Materials and equipment:

- 1.3kg of resin (100:30 ratio of resin/hardener) Epikote 04908.
- Release agent (wax).
- Isopropanol alchohol.
- 5 m5 7cm+ nuts and bolts.
- Flow mesh.
- Breather material.
- Vacuum bag in which entire mould can fit.
- Vacuum tube to use as a bladder.
- Tacky tape.
- Tube.
- Clamps.
- Vacuum pump.
- 4cm diameter carbon fibre 3k ±45 braid for over the bladder.
- 7cm diameter carbon fibre 3k±45 braid to use as inner rim.
- Tin brackets with the cross sectional shape of the mould to form the carbon.
- 4 outer mould pieces from aluminium.

Process:

- The mould is cleaned on all surfaces.
- Wax is put on the surfaces that are going to be in contact with resin, so all surfaces.

- The aluminium outer moulds are processed with marbocoat release agent four times.
- The two parts of the mould are attached to each other with the nuts and bolts.
- The carbon fibre braid is cut to 2m, and the width of the braid is tried to be broadened.
- The bladder is cut to 2m, one end is closed with tacky tape. The other end has a tube inserted for pressure control during infusion.
- Lay the carbon fibre in the mould, ensure the carbon fibre stays in the desired position using the tin brackets, and do not apply too much force to keep fibre alignment as proper as possible. Figure 54 illustrates this method.

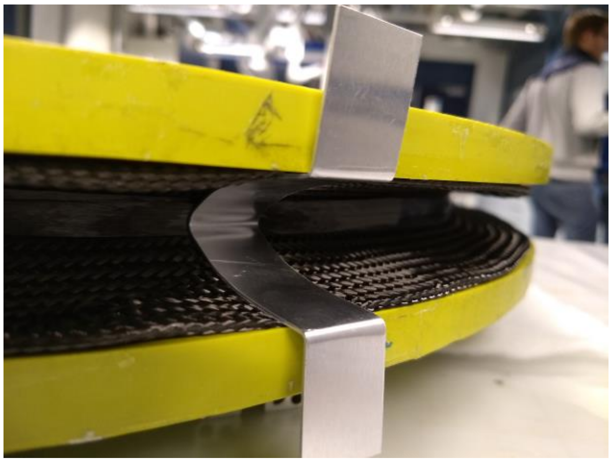

Figure 54: Outer braid of carbon fibre and the UD stiffener held in place by a bracket during production

- Pull the smaller diameter braid over the bladder.
- Place the bladder and braid combo in the mould, inflate the bladder afterwards to see if it is placed properly.
- The exit and entrance of the infusion tubes are decided to be across from each other, the resin can then flow evenly from the entrance to the exit along both sides of the mould. The exit tube for the bladder is next to the exit tube for the resin.
- Place the outer moulds on the inner mould, taking care that the outer mould has a proper connection with the inner mould as for the resin not to be able to seep out.
- In order for the entire rim to be filled with resin, take bleeder material and guide it to the edge of the vacuum back to the exit tube. If the exit tube would be near the rim and filled too soon, one side of the mould might not get wetted totally.
- Protect the holes, bolts and edges on the mould with tape and breather material to ensure that the vacuum bag does not tear.
- Put breather material around the mould in the empty parts of the vacuum bag in order to ensure the trapped air can be sucked out to create the vacuum.
- The entrance tube ends close to the edge of the vacuum bag, use flow mesh to create a way for the resin to get to the carbon fibre in the mould.
- The exit tube also ends close to the edge of the vacuum bag, use breather material to create a path to the mould. This way, as long as the resin does not reach the exit tube, the mould will be under vacuum and resin will be pulled through the material. Having the exit tube as far from the

mould as possible gives the resin more time to flow through all of the material and reduces the chance for dry spots.

- Apply tacky tape on the edges of the vacuum bag and close the bag. Put extra tacky tape around the tube so there is less likely to be a gap or leak around the tube.
- Ensure that the exit tube will not be closed due to pressure.
- Connect to the vacuum pump and check for leaks.
- Guide the bag such that the bags connect in the middle of the mould while slowly pulling a vacuum, see if the fibres and all layers are positioned as desired. This way the bladder has the most even shape resulting in a nicer rim.
- Mix resin, 1.3kg, 100:30. 1000mg of resin, 300mg of hardener
- Degas resin for 30min with a sponge of scotchbrite to give a nucleation site.
- During 30min, keep testing if vacuum bag is still whole and if all air has exited the mould and bag.
- After degassing put the bucket with resin in a bucket of water, to ensure that the resin does not over heat during infusing and curing.
- Place the exit tube over a high standard, this way there is a smaller chance the resin will end up in the pump, also make sure there is a bucket in the resin catcher of the pump setup.
- Infuse at 50 millibar, this is to have smaller bubbles in the resin, since degassing is done at 10 millibar or below.
- After the entire product is visibly wetted and there is enough excess resin in the exit tube to account for backflow, cut of the resin and let the pump on overnight at 500mBar.
- When the resin is relatively hard, take away the pump.
- Let part cure for at least 24h total, as is stated in the resin data sheet.
- Take the part out of the mould.

B.9 Test 8: Materials, Equipment and Process

Materials and equipment:

- 1.95kg of resin, 1.5kg of Epikote and 0.45kg of Epikure. (100:30 ratio of resin/hardener) Epikote 04908.
- Release agent (wax).
- Marbocoat Release agent.
- Isopropanol alchohol.
- 5 m5 7cm+ nuts and bolts.
- Flow mesh.
- Breather material.
- Vacuum bag in which entire mould can fit.
- Silicon bladder.
- Tacky tape.
- Tube.
- Clamps.
- Vacuum pump.
- 4cm diameter carbon fibre 3k ±45 braid for over the bladder.
- 7cm diameter carbon fibre 3k±45 braid to use as inner rim.
- Tin brackets with the cross sectional shape of the mould to form the carbon.

- 4 aluminium outer mould pieces.

Process:

- The mould is cleaned on all surfaces.
- Wax is put on the surfaces that are going to be in contact with resin, so all surfaces.
- The aluminium outer moulds are processed with marbocoat release agent four times.
- The two parts of the mould are attached to each other with the nuts and bolts.
- The carbon fibre braid is cut to 2m, and the width of the braid is tried to be broadened.
- The bladder is cut to 2m, one end is closed with tacky tape. The other end has a tube inserted for pressure control during infusion.
- Lay the carbon fibre in the mould, ensure the carbon fibre stays in the desired position using the tin brackets, and do not apply too much force to keep fibre alignment as proper as possible.
- Pull the smaller diameter braid over the bladder.
- Place the bladder in the mould, inflate the bladder afterwards to see if it is placed properly.
- The exit and entrance of the infusion tubes are decided to be across from each other, the resin can then flow evenly from the entrance to the exit along both sides of the mould. The exit tube for the bladder is next to the exit tube for the resin.
- Place the outer moulds on the inner mould, taking care that the outer mould has a proper connection with the inner mould as for the resin not to be able to seep out.
- In order for the entire rim to be filled with resin, take bleeder material and guide it to the edge of the vacuum back to the exit tube. If the exit tube would be near the rim and filled too soon, one side of the mould might not get wetted totally.
- Protect the holes, bolts and edges on the mould with tape and breather material to ensure that the vacuum bag does not tear.
- Put breather material around the mould in the empty parts of the vacuum bag in order to ensure the trapped air can be sucked out to create the vacuum.
- The entrance tube ends close to the edge of the vacuum bag, use flow mesh to create a way for the resin to get to the carbon fibre in the mould.
- The exit tube also ends close to the edge of the vacuum bag, use breather material to create a path to the mould. This way, as long as the resin does not reach the exit tube, the mould will be under vacuum and resin will be pulled through the material. Having the exit tube as far from the mould as possible gives the resin more time to flow through all of the material and reduces the chance for dry spots.
- Apply tacky tape on the edges of the vacuum bag and close the bag. Put extra tacky tape around the tube so there is less likely to be a gap or leak around the tube.
- Ensure that the exit tube will not be closed due to pressure.
- Connect to the vacuum pump and check for leaks.
- Guide the bag such that the bags connect in the middle of the mould while slowly pulling a vacuum, see if the fibres and all layers are positioned as desired. This way the bladder has the most even shape resulting in a nicer rim.
- Mix resin, 1.95kg, 100:30. 1500 mg of resin, 450 mg of hardener.
- Degas resin for 30min with a sponge of scotchbrite to give the mix a nucleation site.

- During 30min, keep testing the vacuum bag for leaks and if all air has exited the mould and bag.
- After degassing put the bucket with resin in a bucket of water, to ensure that the resin does not over heat during infusion and curing.
- Place the exit tube over a high standard, this way there is a smaller chance the resin will end up in the pump, also make sure there is a bucket inside the pump assembly that can function as a resin catcher of the pump setup.
- Infuse with the vacuum pump at max vacuum that is achievable. This is to have the bladder exert as much pressure as possible from the inside, as voids are not a problem at this stage of testing.
- When the part is fully wetted keep the pump at the lowest pressure, to ensure that the bladder keeps maximum pressure on the inside during curing.
- When the resin is relatively hard, take away the pump.
- Let part cure for at least 24h total, as is stated in the resin data sheet.
- Take the part out of the mould.

C: Closed cell foam as core material

A single sheet could produce enough material for 7 wheels, and an added weight of 150 grams per wheel. At a cost of 50 euros per sheet, this would add a total material cost of around 7 euros per wheel on material. Ofcourse the foam would have to be cut or milled into the correct shape, which adds more labour and equipment costs. Foam cores might make the part heavier overall, but it might make the part faster to manufacture as well. A foam core could lead to full automation, which then reduces the production cost. The foam core rim could then be an entry level, cheaper alternative that has more mass. Automatically producing a curved foam core could be costly and time consuming when milling the foam, due to the double bend nature of the shape. It would be possible to mill the needed bend and the outside curved.
After putting the cores in the mould one could run a mill with 2 diameters through the foam by turning the mould, introducing the gutters for the tire.

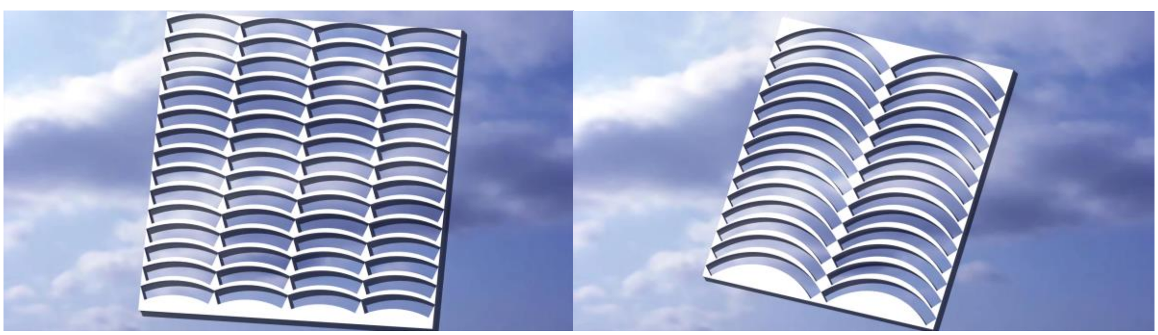

Figure 55: Model of a possible cutting layouts that could be used for cutting foams. Left: Eights of a rim to use the material more efficiently. Right: Quarters of a rim for ease of production, but with more material waste.

A probabilty would also be to create a metal wire or plate with the shape of the cross section that keeps the shape even when heated. This would get rid of all milling, reducing overall cost.
A different solution would be to cut the foam core out of the foam sheet in a straight profile using a hot wire (Hotwire Systems, 2017), as illustrated in figure 56. After the cutting, sections can be taken out of the bottom of the profile in order to be able to make a circle. This way, 24 profiles can be taken out of a single sheet, resulting in enough cores for 12 wheels. This is 56% more than when taking out curved profiles as

are shown in figure 55, but will result in a less precise made product due to the aproximation of a circle instead of milling a circle. If one would make incisions every centimeter in order to create a circular aproximation, a hundred incisions can be made per core. With a hundred incisions, every incisions only needs to bridge 1.8 degrees of deflection in order for the profile to bend into half a circle and it comes down to only a 1.4mm width gap at the bottom of the profile. These incisions however will fill with resin during production, resulting in heavier products.
This process can be automated, resulting in some initial costs, but low overhead.

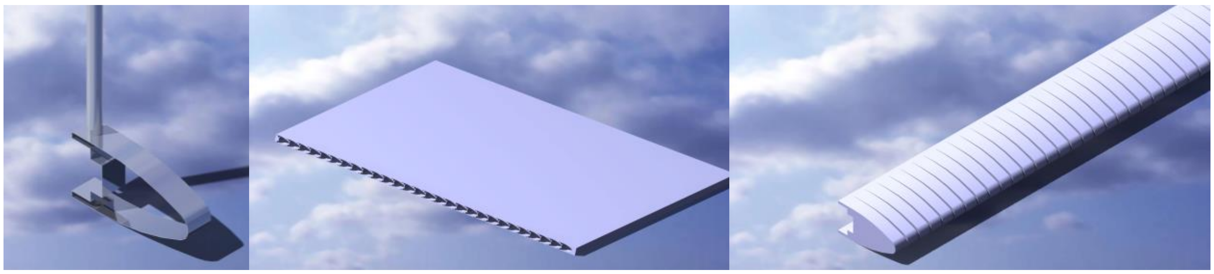

Figure 56: From Left to Right: Model for a foam cutting device. Straight cut foam for maximum material efficiency. Incisions needed every centimetre to be able to bend the cut-out.