A filament wound pillar for a pedestrian bridge



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Abstract

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This report describes the research done on the possibilities of a structural element in the built environment made using the 'coreless' filament winding composite forming technique. The focus lies with the combination of a loadbearing capacity and an aesthetic value specifically derived from this production technique. This is done by the design of a pillar for a pedestrian bridge. The report contains a literature study on both the technique and its common materials. However, the core of the research is done by physical and digital modelling and concluded with physical tests of two types of one to five scaled mock-ups. The first part focusses on the possibilities and aesthetic of the shape, the second part seeks to substantiate the structural probabilities. The result is a design of a pillar with a suggestion for the supports to the bridge deck and the ground. The design seems feasible but further research is needed before the capacities of the design can fully be substantiated and the product can be put in practice. The current obstacles include uncertainties in the used calculation software, the interaction of the different wound bundles and the durability of the composite material. Shown is that an aesthetic value can be gained from the technique and the material whilst maintaining structural capacity. A lightweight product can be constructed and diversity can be achieved according to the described principle.

Keywords: Filament winding, fibre reinforced polymer, light weight pillar, bridge, architecture.

Graduation Committee

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Preface

This report and its appurtenant presentation conclude a 7 year period at the Delft University of Technology. Graduiotion would not have been possible without the help of multiple of individuals to supply me with knowledge and motivate me to push me to my limits. So first I would like to thank my first and secondary tutors for helping me direct my process and the information concerning my topic. Additional aid on structural matters came from ir. Andrew Borgart and ir. Peter Eigenraam from within the faculty and dr. ir. Sotiris Koussios of the aerospace engineering faculty. Special thanks go to Albert ten Busschen of Poly Products for anserwing my questions on composites and showing me around on in the Poly Products workshop.

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I've had a lot of fun during my graduation.

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1. Introduction

Advanced fibre reinforced polymer composites have become more available the last decades due to rapid technological improvements in the material and production techniques (Strong, 2008). One of these techniques is filament winding with which impregnated continues fibre roving is wound around a mandrel or mould. The use of long fibres inherently allows for strong composite materials and the ability to achieve a high fibre volume fraction can improve performance even further. The possibility of a high level automation in the technique reduces production cost additionally increasing the availability (Peters, 2011). The technique is currently used in a broad variety of industries to produce high quality products.

The growing diversity of the winding equipment and the manufactured products has increased the interest in the architectural research. Pioneering in this is a seminar at the Stuttgart University by the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE). The search for aesthetical value derived from expressing the production technique is also clearly exhibited in recent furniture production experiments. At Stuttgart, however, they started investigating other techniques and in the furniture industry only small scale, low quantity projects are undertaken. The advances in the manufacturing technique and materials exhibit architectural potential but little research has yet been done.

The goal of the research is to introduce an (semi-)architectural application in which the technique is used to derive a unique aesthetic value and a substantiated structural capacity to prevent the product to solely become a piece of art. To investigate the possibilities the decision is made to design a pillar for a pedestrian bridge. When the feasibility of the principle is determined the design might be extended to other structural applications.

Methodology

The research includes a large section on understanding the composite material and filament winding technique. The other part is focused on understanding the structural behaviour and aesthetical value of the shape. All segments of the research rely at some point on conversations with specialists. The graduation project started November 2014 and lasted until July 2015.

Understanding the material and technique is done starting with a literature study which focuses primarily on three recent and comprehensive books on composite material and appurtenant production techniques. The secondary step was through the actual manufacturing of composite products. The process of ordering the materials, making the winding equipment and destructive testing afterwards required extensive knowledge of the process and material specifications. Specialist advice came from multiple assistant professors and PhD students form the Architecture faculty and other faculties of the Delft University of Technology (DUT). Additional information from practice came from composite manufactures and material suppliers.

The structural behaviour and aesthetical value are investigated using the parametric design software Grasshopper, structural analysis software Karamba and the production of physical models. The models are discussed with peer students and both graduation tutors.

The report starts with the full result of the literature study on the technique, materials and some reference cases. Then will go to describe the process of determining the shape of the pillar and design constraints and limitations. The third part will describe top and bottom support elements. The fourth part discusses the structural aspects of the proposed design. Starting with the equations and their parameters and concluding with the calculated structural capacity. The fifth part describes the tests done and concludes on the technical feasibility of the pillar. The final conclusion discusses the overall feasibility of the design.

The report includes two appendices in which different aspects are described and shown more elaborately.



2. The technique

In this chapter an introduction to the filament winding composites forming technique and its variations are given. First the basic elements are defined as the terminology sometimes differs in different books and brochures. These definitions given are as they are used in the book Structural Composites Materials (Campbell, 2010). Then a short history of filament winding is given ending in the currently used techniques and equipment. Further depth is reached on the topic of the technique used for thermosetting and thermoplastic resins, the difference between wet- and dry-winding, winding paths and mandrel types. The conclusion is an evaluation of the possibilities for the column.

2.1. Terminology

Filament	Synonymous with fibre
Strand	Bundle of untwisted filaments, primarily used for glass fibre
Tow	Bundle of untwisted filaments, primarily used for carbon and graphite fibres
Roving	Bundle of strands or tows collected without twisting
Yarn	Bundle of strands or tows collected with twisting
Band	Width of multiple roving or yarns next to each other when processed
Таре	Band with the roving or yarns held together with a solidified thermoplastic matrix
Prepreg	A with resin pre-impregnated roving, yarn or band
Towpreg	Prepreg with carbon fibres reinforcement
Spool	Roll of fibres which can be unwind easily, synonymous for reel and bobbin
TEX	Unit to indicate linear mass of a fibre or fibre bundle in gram per kilometre

Fig 1 shows a typical wet winding flatbed configuration with its different components.

2.2. Introduction

Filament winding is a composite forming technique where continues fibres impregnated with a resin are wound onto a rotating mould. The first experiments with composite forming through winding were done in the early 1940. The technique was to hand wind glass fibres around a wooden mandrel and paint brushing it with an epoxy resin. In the following years the process became more automated and industrialized resulting in larger and faster machines that could handle up to thirty spindles in one batch. The axis of rotation increased from two to four or more, increasing precision, speed and form-freedom. Current industrially produced products by filament winding include: pressure vessels, drive shafts, storage tanks, sport articles and pipes including knee- and T-parts (Peters, 2011). Other products which are not industrially produced and more of an experimental nature are airplane fuselages (Strong, 2008), chairs and bicycle frames (Peters, 2011). Because of the tension on the fibres during winding re-entrant shapes are not possible.

Primarily, a two axis of motion winding machine was sufficient; mandrel rotation and the winding head movement parallel to the rotation axis. Nowadays the flatbed configuration (horizontal axis for mandrel rotation) has three to four axes of motion and the



Fig. 1: Typical wet-winding flatbed configuration

gantry configuration (vertical axis for mandrel rotation) can have up to six. In these machines the higher amount of axes increase the precision and the possibility of shapes such as T's and knees (Advani & Hsiao, 2012). Even higher amount are commercial used but this is done to increase speed as a second feeder or to create more complex weaving patterns (Peters, 2011). In some machines it's not the mandrel that rotates but the machine around it. This can be done in a LOTUS system where the mould is going through a circular filament feeder allowing for shapes without a rotational axis like a S-shape (Anderson, 2006). Another system is the multi feed configuration or pull winding configuration where the mould does not move and the fibres are spun while pulled. Recently robotic winding has been introduced using a multipurpose six or seven axes robotic arm with an external axis on which the mandrel rotates. This seems to be less accurate and frequent calibration might be needed (Advani & Hsiao, 2012; Prado, Dörstelmann, Schwinn, Menges, & Knippers, 2014).

Filament winding has the possibility to fabricate elements over 50 m in length for wind-turbine wings (Zoltec) or up to 20 meters in diameter for silos (Plasticon). By using a multi feed configuration or a 360 degree ring delivery system semi-continues tubes can be made, otherwise the technique is bound to discrete production (Advani & Hsiao, 2012).

2.3. Characteristics

The production technique is determined by the different aspects as described below. They are either based on material or technical conditions and requirements.

2.3.1. Thermoset or thermoplastic resin

When a thermoset resin is used, the uncured polymer needs an additional curing process after layup. Depending on the resin mixture this can be at room temperature or at an elevated temperature with or without increased pressure. For an elevated temperature different techniques can be applied such as a traditional oven, heat radiation equipment or an autoclave. Curing can require a long and careful process of heating and cooling to prevent residual stress between the different lamina (Advani & Hsiao, 2012). During this process the element might need to be rotated around the horizontal axis to prevent sack of the resin and if that is not possible hanging should be done with the rotational axis of the production vertical to ensure an equal circumferential material thickness (Strong, 2008).

When a thermoplastic is used the resin has to be consolidated. This means a four step procedure that consists in succession of intimate contact, polymer healing, material compaction and finally solidification. Intimate contact in the form of pressure is required to have a contact of the polymeric surfaces where macromolecules can start to penetrate which will result in polymer healing. The compaction will minimize entrapped gas volumes and voids that alter the products properties. Finally the polymer is cooled and solidified. There are two ways to consolidate; the first is a one-step procedure where the fibre bundle with the polymer is locally heated slightly above melting point, applied on the mandrel, pressure is then applied by a roller and the thermoplastic solidifies by cooling. This method requires complex and highly controlled feeding heads and is thus very costly. The second procedure is winding the prepreg around the mandrel and using an oven with a vacuum bag or an autoclave to melt and consolidate it. The one-step procedure has the advantage that the size is only limited to the size of the winding machine. Non-geodesic reinforcing paths can be wound resulting in more design freedom (Advani & Hsiao, 2012).

Filament winding is most commonly done with a thermosetting resin. Extensive research is done on thermoplastics in composites due to some properties which they inherently have, but the use is still limited due to cost and process complexity (Campbell, 2010). The materials are described with more depth in chapter 3: The Material.

2.3.2. Wet-winding or dry-winding

There are two methods for winding; wet-winding in which fibres pass through a resin bath before fed to the mandrel and dry-winding using a, with resin, pre-impregnated fibre bundle called prepreg or towpreg (Abdalla et al., 2007). The resin bath holds an activated liquid thermoset or liquefied thermoplastic. Coming out of the resin bath, the bundle of fibres goes through mechanical rollers or squeezers to enhance wet-out and control the amount of resin on the fibres. After layup final curing on the mandrel is required. An important aspect of wet-winding is the pot life of the resin. For thermosets curing at room temperatures this must be long enough that the viscosity of the resin stays low enough during the whole layup process. To reduce time, thermosets with heat-activated initiators can be used. These need an oven or autoclave or in some cases lamps or other radiating equipment for their curing. Using thermoplastics as a resin in the resin bath has the problem that constant heating is required and the polymer might start to degrade. Another problem is that a resin bath can emit harmful vapours creating a toxic working environment for operators. Using thermoplastic for wet-winding is hardly ever done successfully (Advani & Hsiao, 2012).

Due to the required pre-processing of the prepreg or towpregs dry-winding has a higher material cost than wet winding. A

thermoplastic prepreg is heated at the nipping point where the fed bundle meets the already placed material. This heating zone can have a heat source such as a laser, flame, hot gas torch or infrared radiation. Shortly after that point the thermoplastic consolidates and the process is therefore referred to as a set-while-winding process. A thermoset prepreg has a resin in B-stage and will solidify with elevated temperatures. Using a prepreg allows for an increase of winding speed (Campbell, 2010; Strong, 2008).

2.3.3. Winding path

Three paths for winding can be distinguished; hoop, helical and polar, all of which approximate a geodesic path. These paths are often combined in one element for specific force directions. In hoop winding, also known as circumferential winding, the fibres are placed nearly perpendicular to the rotation axis, the angle is defined by the width of the band or tape so that the fibres are placed nearly perpendicular to the rotation axis, the angle is defined by the width of the band or tape so that the fibres are placed nearly perpendicular to the rotation axis, the angle is defined by the width of the band or tape so that the fibres are placed nearly perpendicular to the rotation axis, the angle is defined by the width of the band or tape so that the fibres are placed nearly perpendicular to the rotation axis, the angle is defined by the width of the band or tape so that the fibres are placed nearly perpendicular to the rotation axis, the angle is defined by the width of the band or tape so that the fibres are placed nearly perpendicular to the rotation axis, the angle is defined by the width of the band or tape so that the fibres are placed nearly perpendicular to the rotation axis, the angle is defined by the width of the rotatial strength of the element. In polar winding the fibres are placed in an angle approximating the direction of the rotational axis. These windings are important for the strength of the elements. All angles between hoop and polar are called helical in which the fibres are offset from the previous loop. They connect the hoops and polar windings and add strength to the ends of the element (Strong, 2008). Polar and helical are both cross winding where fibres cross one another in the composite resulting in different mechanical properties. Following the geodesic path for the layup of the fibres prevents slipping over the mandrel. Using thermoplastics allows for leaving the geodesic path (Advani & Hsiao, 2012). To keep the windings in place either the shape of the element (geodesic path) or littl

Filament winding is currently mainly used for its mechanical properties and relatively low production cost. Therefore winding paths are determined for optimal load distribution. In example, most pressure vessels are helical wound with an angle of 54 degree as this is, according to the netting theory, the ideal fibre angle for their load distribution (Nijssen, 2013). For vertical standing silos, hoop windings are the main direction.

For the actual layup a specific winding path has to be determined which require a high amount of calculation. Fortunately specific software is developed taking the geodesic paths and the hooks at the end of mandrel into account. This software drives all axis direction and speed for a very precise layup. The current high amount of axis was not possible without the use of strong computational power and speed. Different software packages are developed and standardized to work on different machines. Some of these products are: Entec, Cadfil, Etamax, ComposicaD, Cadwind. The main focus is pressure vessels and pipes and some of the packages include elbow and tee shaped elements and can include FEM analysis software. For uncommon filament winding patterns, shapes and mandrels new software is to be created that include winding and tool path generation, simulation of robot kinematics and possibly code generation (Prado et al., 2014).

2.3.4. Mandrel types

Three types of mandrels can be distinguished; mandrels that are used multiple times and mandrels that are lost after production, both used on large scale. The third type is currently being explored containing the adjustable mandrels and core-less mandrels, few examples are currently available.

For the design of a mould multiple aspects are to be kept in mind. Just like all moulds the tolerances of the mandrel determines the precision of the product. Another important aspect is that the outer surface remains uneven as it is not defined by the mould. Mechanical properties might cause problems such as deformation due to the pressure of the winding process and deformation under the weight at slender, large spans. With heavy mandrels the acceleration is to be kept in mind. Also thermal expansion should be taken into consideration, an intermediate layer of elastomeric polymer might be needed (Strong, 2008). To be able to remove a mould, a special layer of release agent is applied on the mandrels prior to layup (Nijssen, 2013).

The first group contains the stiff, collapsible and shape memory polymer mandrels. Stiff and collapsible mandrels are mechanically removed from the element and need to be though and strong enough to do so. The shape often needs to be slightly tapered and its surface smooth. These mandrels can be heated during winding to enhance polymer healing thus increasing mechanical performance (Advani & Hsiao, 2012). Another technique is the memory polymer mandrels which reduce in size when heated. First the polymer is moulded in in the small extractable state. Then, prior to winding, the desired shape of the composite is made by deforming the polymer and rapidly cooling it afterwards. After curing the polymer is heated and shrinks back to its original state. This process can be repeated many times with the same mandrel (Strong, 2008).

The second group includes all single use moulds such as the dissolvable, meltable, breakable mandrels and liners. Dissolvable mandrels can be made of a solid material with a water-soluble binder. Often, sand with a polyvinyl alcohol binder or soluble salts is used. Meltable cores can be made of polymers, low-melting metals and eutectic salts. In case of such a mould the flow temperature and melting point should be somewhere between the products curing temperature and its resistible heat. Mandrels can be made of brittle materials such as plaster and broken out after curing. But the high risk of damage made this less common. Liners are mandrels that stay inside the product. This is regularly done for products with only small openings, if it contains a volatile medium or when higher chemical resistance is required. The liners strength can be increased by inflation during layup (Strong, 2008). It is also possible to use inserts as a mould, these inserts can have a structural purpose or used for joining different elements.

The third group contains the adjustable and core-less mandrels. By reducing the cost for mandrels more form-freedom can be achieved as products are less bound to standardization. One of the solutions is to be able to create several different products by using one single mandrel. Another method is by not using a core or not even a mandrel. During this research no information was found on adjustable moulds. However, experiments were likely done. Core-less winding has the possibility of turning multiple basic "2D" shapes as a mould into a 3D shaped element. Both require intensive use of computer modelling and testing before a strong and woundable shape is created. Two approaches can be distinguished; the first uses straight fibres crossing from end to end in a polar path resulting in the final product. The second is a two-step method where first a straight fibre bundle shape is created that acts as a scaffolding for the second layer using stronger fibres. The method to create a shape without a mandrel is by using a set of points where the fibres can be hooked on. These techniques rely on high degrees or rotational freedom such as 6-axis robotic arms with additional external axis (Menges, 2013) or two robotic arms (Prado et al., 2014). For all core-less windings the pressure on the material for polymer healing should be kept in mind.

2.4. Discussion

To make the filament winding technique attractive for the architecture industry is has to be either low cost or highly aesthetical. By making the elements multifunctional overall cost might be reduced and by allowing high form-freedom aesthetical value might be added. To lower cost, the amount of production handlings should be reduced. All handlings can consist of multiple steps but should be limited to one or skipped completely. Also, the steps should require the least possible human labour. Current steps are:

Mould manufacturing

Using 2D moulds reduces the costs by using cheaper and commonly used production techniques and common materials. Important aspects are the mould extraction possibilities, strength, stiffness and rounded edges to prevent cutting the fibres. An example might be CNC milled plywood. Besides manufacturing, a way to automatically coat and mount the mould to the machine should be determined.

Winding path determination

Using parametric design software with integrated structural analysis is required when creating multiple small batch structural elements for practical reasons. It is highly impractical to individually calculate each element. This means that every element can be different as long as they follow a standardized principle.

Filament layup

A high amount of motion axes mean higher form-freedom but also more advanced equipment. A three axes flatbed winding system might not be suitable for many shapes but might have the lowest equipment cost. For higher form-freedom a gantry system or a robotized system can be used.

Curing

Using thermoplastics allows for setting during winding but require more precise equipment and/or prepregs. Using a thermoset at room temperature is a negotiation of pot life, additional curing time and winding time. All three are related that if one is lowered the other two do too. Using elevated temperature initiators can offer the solution when a simple 'heated room' can be used. In practice this can be done using an electric heat source and a plastic foil or tent. Another aspect to be taken into account using core-less moulds should be the possibility of removing the mould in uncured condition out of the machine. Not being able to do so might result in prolonged occupation of the winding engine reducing output rate.

Mould extraction

There are three ways to reduce mould extraction cost. The first is by making the design for both the product and the mould easy accessible for manual extraction. The second is inventing a system where no mould is needed. The third is leaving the mould as a part of the product. This can be a functionless piece of material or an integrated element such as tubing for installations, joining elements or structural elements.

Optionally using prepregs

By using prepregs winding speed can be increased but material and processing cost will increase too. Also the limitations by the pot life can be eliminated.

3. The material

In this chapter the conventional filament winding materials are discussed. First the fibres, then the matrixes and at the end possible additives and such are described.

3.1. Fibres

Material wise, elements formed by filament winding are identical to most fibre reinforced polymers (FRPs) with the difference that only continues fibres can be used. Most common used fibres are glass fibres and carbon fibres. Other fibres include aramid fibres, Ultra-high Molecular weight Polyethylene and basalt fibres. Organic fibres are unlikely to be used as they are staple fibres thus less able to deal with the tensional force applied during winding and has other mechanical complications (Nijssen, 2013; Strong, 2008). Combinations of different fibres in one product can be done for mechanical or financial reasons (Menges, 2013; Prado et al., 2014). The fibres are stronger and stiffer than the polymer matrix therefore they normally carry the tension in the product. Fibres are never used without a matrix.

3.1.1. Glass fibres

Most glass fibres have letter designations to imply product specific qualities which derive from different chemical propositions as shown in the table below (Wallenberger, Watson, & Li, 2001). E-glass, S-glass and quartz are most commonly used. E-glass is least expensive but provides a good combination of high tensile strength and young modulus. S-glass is 40 percent stiffer but more expensive. Quartz is mainly used for its low dielectric properties (Campbell, 2010).

Abbreviation	Designation	Property or characteristic		
Е	Electrical	Low electrical conductivity		
S	Strength	High strength		
С	Chemical	High chemical durability		
Μ	Modulus	High stiffness		
Α	Alkali	High alkali of soda lime glass		
D	Dielectric	Low dielectric constant		

Glass fibres are very susceptible to degradation from exposure to air and mechanical abrasion, therefore they are always coated. This is called sizing and accounts for 0,5 to 5 percent of its weight. This coating is, or is otherwise further in the process replaced by, a surface finish to improve the fibre to matrix bond. These coupling agents are essential for the performance of the composite final product but different resins require different sizing. Information on the compatibility comes with the product and should be taken into account when selecting the fibres (Campbell, 2010; Nijssen, 2013).

As a single fibre has only a thickness between 5 and 30 micrometre, a bundle of fibres is spun into a strand consisting of 51 to 1624 filaments prior to further processing. The strand is further processed into a yarn or roving where in a yarn the bundle is twisted thus has lower mechanical properties but higher flexibility. Spools come in different weights with different TEX (gram per kilometre) depending on their purpose (Campbell, 2010). This TEX is different depending on the next step in processing. A TEX between 600 and 9000 consisting of 2000 to 4000 filaments per strand is widely used for filament winding. For knitting, pulltrusion, weaving and chopping, larger or smaller bundles can be used. Common spools have multiple kilometres of roving or yarn. For example: a 10 kilogram spool with a TEX of 500 has 20 kilometre of roving or yarn. The amount of twists in a yarn is between 5 and 100 per meter.

Sales brochures of multiple suppliers show that most products come with specific requirements for the machining environment. For example: the advised temperature for '3b fibreglass direct roving' during winding should stay between 20 °C and 23 °C with a relative humidity of 60 to 65 percent. The spools should be left to condition for over 24 hours before use. Furthermore, regular storage should be done in a dark cool place and is limited to a couple of years.

Manufacturers include: Fiber Glass Industries, PPG Fiber glass, 3b-fibreglass, Saint-Gobain

3.1.2. Carbon fibres

Generally there are three precursors to produce carbon fibre. Polyacrylnitril (PAN) is the most common used and has more consistent mechanical properties but is more expensive than pitch. The pitch used derives from petroleum. Both isotropic and mesophase pitch is used and the theoretical mechanical, electrical and thermal properties are better but due to imperfections and variations this is reduced in practice. The third precursor is rayon which is made of cellulose extracted out of natural material such as wood pulp. Currently it only amounts for 1 to 2 percent of the market but this might increase due to the low precursor cost for the fibres (Dumanlı & Windle, 2012). The stiffness of the fibres can be increased by a graphitization process. However, due to the significant increase in costs, this is only done for the space industry (Campbell, 2010).

Carbon fibres without surface treatment do not bond well with epoxy. Therefore the surface is treated to remove weak outer layers and etch the surface for a bonding agent. An additional layer of sizing is applied that different from glass fibres does not act as a coupling agent. This layer only consists of 0,5 to 2 percent and is mainly applied to protect the fibres from mechanical abrasion (Campbell, 2010).

Carbon fibre spools are made of an untwisted bundle of fibres called tow. Tows come in different sizes ranging from 1000 fibres/tow up to 200,000 fibres/tow. Normally this is shortened by using a thousand fold (k), for example 24,000 fibres/tow is called a 24k tow. Tows for the winding process usually start from 12k (Campbell, 2010).

Manufacturers include: Toho Tenax, Cytec industries, Formosa plastics, Hexcel, Mitsubishi Rayon, SGL Carbon, and Toray industries Zoltek.

3.1.3. Other fibres

Aramid fibre

Aramid is the group name for aromatic polyamides more commonly known under the brand names Kevlar and Twaron. Aramid fibres are most used for products that require high impact strength but low weight such as body armour, helmets and sports articles. Due to the lack of suitable fibre to matrix bonding agents aramid fibres perform relatively poor on longitudinal compression and interlaminar shear. The fibres also have the tendency to absorb moisture but are inherently flame-resistant (Campbell, 2010).

Trade names include: Kevlar, Technora, Twaron, Heracron

Ultra-high Molecular weight Polyethylene Fibres (UHMWPE)

Thermoplastic fibres with a high impact resistance and a mass of 970 kg/m³ but the maximum service temperature of 95 °C and the high cost make application in the built environment unlikely (Campbell, 2010).

Trade names are: Dyneema and Spectrum.

Basalt fibres

Made in a process that is similar to glass fibres but has higher mechanical properties and is more expensive. The fibres are made purely from melted basalt rock thus the control of the purity and consistency is more difficult. Other specific properties are the natural resistance against UV-radiation, high heat resistance and it has no reaction with water or air (Nijssen, 2013).

Trade names include: Basfiber, Technobasalt, Sudaglass Fiber Technology and Kamenny Vek.

3.1.4. Comparison

A comparison can be made for the different fibres. This comparison is an estimate and derived from multiple sources, it can therefore only be used as an indication.

	Unit	E-glass	Carbon	Aramid	Basalt	UHMWPE
Strength	MPa	2400-2800	2000-5300	3100-3600	1430-4900	2000-3000
Elastic modulus	GPa	70-80	160-440	60-80	71-110	110-170
Mass	kg/m ³	2500-2600	1800-2000	1540	2500-2890	965-975
Mass per length	TEX	600-8800	100-3200	22-6500	68-600	75-6222
Cost	Relative	1	13	8	1,5	50
Thermal expansion	mm/mK	5,4 e-3	0,5 e-3	-3 e-3	5 e-3	-12 e-3
Fibre thickness	μm	13-31	5-10	12-20	10-22	12-20
Elongation at break	%	2,6	1,0-1,8	1,7	3,2	2,9-4,5
Colour		translucent/ white	black	yellow	black	translucent/ white

3.2. **Resins**

Filament winding allows for most generally used resins. The main function of the resin is to transfer and distribute the forces over the fibres, protect the fibre against external influences and to keep the products shape. The polymer resins can be divided in thermosets and thermoplastics. Thermoplastics are less used in filament winding due to their high viscosity; this requires higher pressures and highly controlled temperatures (Campbell, 2010). The advantages of thermoplastics include weldability and repairability and absorb in general less moisture. Thermoplastics are mainly used as pre-impregnated fibres called prepregs or towpregs (Advani & Hsiao, 2012; Campbell, 2010). Thermosets can set at room temperature or elevated temperatures depending on the initiators that are added.

3.2.1. Thermosets

The most commercially common used matrixes are polyesters, vinyl esters and epoxies. For specific properties or high performance other thermosets are used such as bismaleimides, cyanate esters, polymides and phenolics. Those often cost more or require higher curing temperatures. Thermosets can also be categorized in addition-curing polymers and condensation-curing systems. Condensation-curing polymers give off water vapour and/or alcohol as a by-product where addition-curing polymers do not. The by-product should be removed from the product to prevent voids or porosities in the composite. Therefore, using condensation-system is more difficult. The addition-curing polymers include the polyesters, vinyl esters and epoxies, the phenolics are condensation-curing systems (Campbell, 2010). The solidification of most thermosets is an exothermic reaction (Nijssen, 2013).

The joining possibilities of thermoset elements are adhesive bonding and mechanical fastening. When applying a thermoset to a metal a coating should be used to prevent possible oxidation by the catalysts. Epoxy generally bonds better with other materials such as wood and metal (CES)

Polyester

Polyesters are relatively cheap and extensively used for commercial products. However, they have relatively poor mechanical properties, temperature capabilities and exhibit relatively high shrinkage during cure. Polyester products are made with three ingredients. For the larger part, around 60 percent, this is a polyester, around 35 percent of a crosslinking agent and 1 to 4 percent inhibitor (Nijssen, 2013). Crosslinking agents are essential for curing but can have additional properties such as lowering viscosity, improve weatherability and act as a flame retardant. For these reasons alterations in the ingredient ratio can be made (Campbell, 2010). The most common crosslinking agent is styrene. The polyester and crosslinking agent form the final matrix. Prior to processing an initiator mostly proxide (MEKP) is added to the mixture, this is a catalyst for the reaction in which the matrix is formed. This reaction can be slowed down using a retarder such as NLC 10. Even without the initiator the chemical reaction forming the matrix occurs, this determines shelf life. This process can be reduced by adding inhibitors but that in turn requires the use of an heat initiator (Nijssen, 2013).

As polyester is a semi-transparent and has a refractive index nearly similar to E-glass fibre it is possible to create translucent greenish composites. An important aspect to achieve optimal result is the removal of air pockets inside the composite.

There is a scale of chemical resistant polyester resins called in upwards order ORTHO, ISO, ISO-NPG and Tereftalic polyester. ORTHO and ISO are the most extensively used in commercial production.

Vinyl ester

Vinyl esters are very similar to polyester but have lower crosslink densities as connection between the different agents is only possible at the ends of the molecule. Therefore most vinyl esters are tougher than polyesters, shrink less when curing and exhibit higher resistance to water and chemicals (Campbell, 2010). Vinyl esters tend to become yellowish over time (Nijssen, 2013).

Epoxy

There are hundreds to thousands different epoxies on the market due the high diversity of resins and curing agents. Epoxies usually perform better on most aspects compared to polyester and vinyl ester because of their high yield crosslink structures. Therefore the material is especially used for high-performance products. A solid epoxy matrix is formed by combining multiple epoxies with one or more curing agents. Often next to the major epoxy multiple minor epoxies are added to influence viscosity or mechanical properties. The most commonly used epoxy for filament winding is diglycidyl ether of Bisphenol A (DGEBA) due to the different viscosities in which it is available (Campbell, 2010). Like polyester, epoxy can be translucent.

During curing most shrinkage will be done when the resin is still in a liquid state, therefore the contraption on the mould can

be less than 2 percent instead of the original 5 percent (Nijssen, 2013).

Phenol

Phenolic resins have higher resistance to heat but often are more brittle compared to the esters and epoxies. Phenol is a condense-curing system, therefore a more difficult to process. Processing phenolic resins releases toxic vapours during processing. The biggest advantage of phenolic resins is that it does not burn and emits very little smoke (Nijssen, 2013). A disadvantage is that the material is inherently brittle and exhibits large contraption and high pressures an temperatures are required for forming (Campbell, 2010).

Typical uses include airplane interiors due to the low smoke emission and in plywood and MDF sheets.

3.2.2. Thermoplastics

The main difference between thermoset and thermoplastics is the crosslinking between the polymer molecules. In a thermoset, a chemical reaction allows the shorter molecules to crosslink forming a polymer matrix, in thermoplastic polymer longer molecules reorder to form a matrix but molecular crosslinking does not occur. The longer molecules also increase the viscosity of the melt making it difficult to process in composites. Processing thermoplastics require higher temperatures and pressures (Nijssen, 2013). Therefore, the use of thermoplastics is limited to a handful in commercial and military production applications. Not having crosslinks mean that thermoplastics are inherently tougher than thermosets but advances in the thermoset industry created equally tough thermosets (Campbell, 2010).

Other advantages of thermoplastics compared to thermosets can be the low water absorption, it is less toxic during processing, has good joining possibilities and is theoretically reusable. However, in practice many challenges in forming have to be overcome and by reheating the material potentially degrades reducing reusability. The additional joining possibilities that thermoplastics can offer are melt fusion, resistance welding, ultrasonic welding and induction welding.

3.2.3. Comparison

A table of comparison for the matrix materials is created. This comparison is an estimate and derived from multiple sources, it can therefore only be used as an indication.

	Unit	Polyester	vinyl ester	Ероху	Phenol
Strength	МРа	40-85	50-80	60-80	28-50
Elastic modulus	GPa	2,4-4,5	3-3,5	3,5	2,8-5
Density	kg/m ³	1200-1500	1100-1400	1100-1400	1240-1320
Material cost	EUR/kg	1,72-1,89	medium	2,47-2,72	1,24-1,4
Processing difficulty		low	low	medium	high
UV-resistance	Relative	good	good	fair	good
Chemical resistance	Relative	acceptable	acceptable-good	good	good
Impact strength	Relative	low	medium	high	medium
Contraction	%	6-8	5-7	<2	high
Thermal expansion	mm/mK	140 e-3		100 e-3	122 e-3
Glass temperature	°C	150-210		67-167	170-270
Maximum service temp.	°C	112-128		122-138	142-157

3.3. Additives

Filament winding is often done without additives other than required for the production process. Minor additives such as pigments are possible. Larger quantities or particle sizes can reduce performances (Campbell, 2010).

The resin can be coloured using pigments. Polyesters and epoxies can be translucent thus allowing more colouring. Due to the inherent tint of these resins colouring is mostly done by gel coating. Gel coating can be applied on the mandrel prior to winding or as an additional brushed layer after winding. Both are additional steps in the process, rarely ever done for esthetical reasons in the filament winding technique.

Fire retardants can be added to the resin in two ways. The first and most extendedly used is adding halogen atoms to the polymer mixture. The halogens unite with hydrogen atoms and creating a smoke that smothers the fire. However, this smoke is hazardous and reduces sight. The other method is to add aluminium tri-hydrate (ATH) to the mixture that is trapped in the matrix. This is a relative cheap solution that does not add hazardous content to the smoke (Strong, 2008). The down side is that it negatively influences the matrix performance when used in high quantities.

3.4. Prepregs

Multiple problems associated with liquid resins in the filament winding are eliminated when using prepregs. The process no longer requires a resin bath so there is more control over the wet-out, fibre to resin ratio, resin viscosity and less resin drips off during winding. Prepregs is possible for both thermoplastics and thermosets. A general problem with prepregs is the need for pressure to remove the air between the laminates (Strong, 2008).

There are four types of thermoplastic prepregs used in filament winding; commingled yarn, bicomponent fibres, powder impregnated and fully consolidated tapes. A commingled yarn is a bundle of both re-enforcement fibres and thermoplastic fibres. Bicomponent and powder impregnated fibres are a pre-processed but unconsolidated product. The fourth product is the fully consolidated tape where a band of fibres and thermoplastic are made to a semi-finished product (Advani & Hsiao, 2012). The products have nearly unlimited shelf life as long as they are kept in the dark and with low relative humidity (Campbell, 2010).

Thermosetting prepregs work with the b-stage of the thermoset resin. The b-stage of a thermoset is where it starts to chemically react and therefore becomes tacky and has higher viscosity. Therefore post-curing at an elevated temperature is required as well as storage time is limited and needs to be done at lowered temperature (Campbell, 2010).

3.5. Treatment for insertions

When making a composite element additional objects are required to dictate the shape, this can be a removable mould or a lost mould. Both require a different surface treatment prior to winding and dictate some specific designing. When the lost mould becomes an integrated functional part, extra care might be needed in choosing the joining method. Like the sizing of fibres each resin might have specific requirements for surface treatment and the bonding agent if any (Nijssen, 2013).

For removable moulds a release agent such as wax is applied. Initially this agent should be applied several times prior to process, however this number can decrease after the mould is used often. Other release agents can be silicone based or, normally before the first time the mould is used, polyvinyl alcohol (PVA) (Strong, 2008).

To integrate an object of a different material in a composite product, surface treatment can enhance the connection but can also prevent the different materials to chemically react with one another. To increase the connection prior to winding the object should be cleaned (including degreasing) and the surface area increased by mechanical or chemical abrasion.

3.6. Conclusion

Probably the most powerful aspect of composite production is the ability to precisely control the properties and behaviour of the finished products. Decades of research allowed for many different fibre types and a multitude of matrixes nowadays. Driven by advances in the high demanding industries such as military and aerospace even more options are added. To manufacture a high quality product extensive knowledge of the materials is required. However, high performance materials are costly thus less likely for architecture in the current building practice.

The most probable materials to be used for the filament wound column are glass fibre and a vinyl ester matrix. Vinyl esters have high impact strength and good resistance against weather influence like epoxies but are cheaper. The main concern with most polyesters is the influence of moisture on its structural properties and durability.



4. Case studies

In this chapter some case studies will be discussed. For each case the design approach, used technique, used material, winding path and some details are evaluated. There are also some patents on filament wound columns but it does not seem that they are commercially produced and are therefore not studied.

4.1. The 'Classical' Column

Somewhat surprisingly, the idea of a filament wound column has been commercially applied for classical columns, exclusively in the USA or so it seems. Multiple manufacturers are producing them and all are specifically focusing on the classical columns. The information is solely retrieved from what the companies expose on the internet and seem not reliable.

The suppliers investigated are: Worthlington products (WP), Fibreglass Specialties (FS), First Class Building Products (FCBP) and Pacific Columns (PC). These were chosen for their information on the internet was most accessible and complete.

Design approach

On the design approach only assumptions can be made. All suppliers advertise the low weight as their main advantage. It is mentioned as being cost efficient because of its quick installation and no large machinery is required. The low weight is also less demanding for the foundations possibly eliminating the need on some soils. The slightly tapered shape of the shaft of the column might have influenced the decision to make it a classical column. This tapered shape derives from as specific aspect of the production technique; the extraction of the mandrel. The typical use seems to be porches, patios and interior decorations (fig 2). The ornaments seem to be glued on. All suppliers state that the columns should be coated and maintained but some offer life time warranty.

Used material, technique and winding path

All manufacturers use glass fibre reinforcements with a polyester matrix. The technique used is probably a wet-winding on a flatbed configuration considering limited diameter and low cost. All columns seem to have a combination of 45 degree (helical) and 90 degree (hoop) winding paths. This is, however, not visible at the exterior surface as it is processed to be smooth.

Specifics

The different data derived from the suppliers' data sheets is shown.

Supplier	H _{max}	Diameter	Wallthickness	Load _{max}
	[m]	[m]	[mm]	[kg]
FCBP	7,3	0,9	4	15000
PC	7,3	0,9	4	13000
FS	-	0,9	5	35000
WP	-	0,9	10	15000



Fig. 2: Filament wound columns

The actual data remains unclear as parameters like wall thickness and loadbearing capacity differ significantly or is not mentioned. This can mean that only few tests have been done to test the structural capacity as it is rather approached as a decorative element.

4.2. The ICD/ITKE University of Stuttgart pavilions

At the University of Stuttgart the Institute for Computational Design (ICD) collaborate with the Institute of Building Structures and Structural Design (ITKE) researching the possibilities of robotics within architecture and building system manufacturing. Two pavilions where made using filament winding. One of the main aspects of the studio is to design and build a research pavilions within a year as it is part of an academic program. The team consists of academics and master students with the leading professors Menges (ICD) and Knippers (ITKE), adding up to a total of around 10 to 20 people.

The design and manufacturing process have been described and published in both cases. For the 2012 pavilion the publication in the Computer-Aided Design journal (Reichert et al., 2014) is used. For the 2013-2014 pavilion the publication in the Robotic Fabrication in Architecture, Art and Design 2014 (Prado et al., 2014) is used. The images are retrieved from the ICD/ITKE website.



Fig. 3: The reseach pavilion after completion in 2012

4.2.1. The 2012 Pavilion

The research pavilion (fig 3) is eight meter in diameter and four meter in height and constructed as one single monocoque structure.

Design approach

The design is based on the biomimetic principle in both shape and material selection. The monocoque structure is based on a combination of lobster exoskeletons (Weigele et al., 2013). From their research in the microstructure of the material of this shell, the idea of using layers of fibres had derived. For the material layup filament winding seemed to be offering the most freedom within the available budget.

Used technique

Wet winding was chosen, however a special configuration was developed. Instead of a conventional mandrel or male mould a discrete steel frame with plywood sheets was used. This mould was placed on a rotation system that acted as an external axis of motion significantly increasing the possible size (fig 4). The payoff was placed on a robotic 6 axis of motion arm.

For the design different software was used for defining the shape, FEM analysis and kinematics for the winding equipment, some of which were specifically customized for the design.

Used material

The reinforcement materials used were a glass fibre roving with a TEX of 4800 and 50k carbon fibres with a TEX of 3300. The amount of fibres is approximately 60 kilometres of glass and 30 kilometres of carbon fibre. The matrix was an epoxy with sufficiently low viscosity to be processed for 12 hours. Curing was done by elevating the temperature to 80 °C for 10 hours. The total weight of the pavilion including resin is 320 kilograms. The average thickness of the shell is 4 mm.



Fig. 4: The winding proces consists of a robotic arm and an external axis for mould rotation. The white bundles consist of glass fibres and the black hold the carbon fibres.



Fig. 5: Detail of the plywood mould and pay-out eye.

Winding path

Multiple winding paths are combined to construct the shape. A glass fibre layer is wound first that would act as scaffolding for the following layers of glass and carbon fibres. The winding paths controlled the structural behaviour of the pavilion but are designed in an asymmetrical way so that two of the five sides are closed for architectural reasons. The carbon is placed over the glass fibres so that the fibres are curved creating a double curved shape. The direction of the carbon is mainly vertical from the foot points up to the top. The total winding time is estimated to 130 hour.

Details

The connection with the ground is made using integrated steel elements. These elements were part of the mould so that they are strongly connected and no post-processing was needed.

Discussion

In the academic article written on the design and production of the pavilion the challenges are mentioned (Reichert et al., 2014). The biggest challenge is controlling the tension on the fibres required during winding. Stated is that it is influenced by winding speed, fluctuations in viscosity of the resin, the amount of resin in the bath, the angles between bath, effector and structure.

Another challenge is the consistency of the wet-out as it is influenced by winding speed, viscosity of the resin, amount of resin in the bath and the surrounding temperature and relative humidity.

4.2.2. The 2013 pavilion

The 2012 pavilion is constructed as one piece which has the disadvantage, if to be used commercially, of limitations in size due to pot-life, manufacturing equipment and transportation. The 2013-2014 pavilion (fig 6) uses filament winding to produce 36 smaller elements to be assembled to form the pavilion. The total area covered by the pavilion is 50 square metres (ICD/ITKE website, 2014).

Design approach

The design is based on the shell of a flying beetle, on micro level it consisted out of smaller pockets encapsulated by fibrous material that is both light and strong. Another aspect of the design is the research towards the automation in manufacturing the different elements. The design includes a diversity of individual elements thus automating shifting the shape of the mould was incorporated as a production process aspect. The process should have the ability of being commercially applicable.

The elements are designed to act as a sandwich panel system where the loads are distributed perpendicular to the rotational axis of the elements.

Used technique

Wet-winding was used with an impressive two times six axis industrial robotic arm configuration (figure 15). The arms collaborated to form a rotational axis that moved synchronised during winding. However, they individually moved to alter their moulds in a semi-automated process. The effectors are adjustable to various component geometries up to diameter of 2.6 meter, with a complexity of up to 14 vertices with the moulds not being planer.



Fig. 6: The research pavilion after completion in 2013.



Fig. 7: The configuration with the two robotic arms and the resin bath underneath.



Fig. 8: The weight of the elements allowed for assembly by hand.

Used material

For the project glass and carbon fibres were used as reinforcement. No specifics are given on the matrix. The maximum weight of an element was 24,1 kilogram with the whole pavilion weighing 593 kilogram (ICD/ITKE website, 2014).

Winding path

Each effectors held one polygon which were wound together with glass fibre. With a total amount of six layers each element is made. The first layers are made with straight connections between the polygons. Then layers of carbon fibre are bended over the straight fibre connections to create a double curved woven surface. As the load is placed in the polygons plane the last layer is local reinforcement of that area (figure 16).

The winding time was 8 to 18 hour per element.

Details

A small reinforcement rectangular profile seems to be integrated in the mould and left inside to connect the elements at assembly. However, on the photographs this is hard to verify.

Discussion

Again, the symbiosis of digital and physical modelling and research was done elaborately. It is hard to say if the design started with the filament winding technique and then a suitable metaphor from nature was investigated or the other way around. The project shows an application of light weight structures derived from the technique.



Fig. 9: The three stools by Moorhead & Moorhead use the same mould but different winding paths.

4.3. Stool by Moorhead & Moorhead

Designers from all over the world have been experimenting with filament winding, mostly furniture. The material used is often carbon fibre in epoxy. Due to the small scale and the design aspect of being as light and thin as possible the relatively high material cost is accepted.

Moorhead and Moorhead is a studio based in New York City. Their design of three filament wound stools in 2011 is interesting as three different products derive from one mould (fig 9). The material used is a carbon fibre tow and the matrix material remains unspecified. All three stools use the same amount of material but by altering the winding path the openness of the surface is altered. The loadbearing capacity is probably limited and has not been assessed prior to winding. The mould is mentioned to be reusable and would to be removed through the larger hole at the bottom of the product.

5. Design process and models

In this chapter discusses the evolution of the shape and the means used to investigate them. Detailed information on the physical modelling equipment is described in Appendix A: Handmade equipment. Appendix B: Images of physical models consist of additional images of the physical models.

5.1. Model making equipment, materials and configurations

Two means are used to investigate possible shapes. The Grasshopper plugin for the Rhinoceros software is used as the primary digital environment. The parametric software uses repetitive sequences, deviating from this sequence requires additional programming thus time and is therefore limiting design freedom. The handmade flatbed winding configuration is used to wind models with a length up to 80 cm in height and a maximum radius of 35 cm (fig 10). The winding is done by hand thus allows for a high level of design freedom but an increased risk of unnoticed deviation from the winding sequence resulting in an inconsistent pattern (fig 11 & 12. The parallel use of digital and physical models allows pointing out flaws in either technique. The digital models are essential to establish the winding paths to wind the physical models with.

In the first physical models only acrylic fibres are used, therefore an additional structure is used for the compressional forces. Further in the process composites are used which deal with both tension and compression. To create the composite material the process had to include additional equipment. This includes a dry fibre dispenser or creel, the resin bath and a pay-out eye (fig 13). An additional breaking system should have been made between the creel and the resin bath but had not been built.

During the composite winding process two people are required. The first is the winder who focusses solely on winding. A flaw in the winding pattern or the fibres slipping off a connection point is often not fixable and means starting over again. The second person makes sure that there is enough resin in the resin bath, calls out the winding path and assists in smaller tasks. Due to the toxic vapours of the resin the process could only be done outside or in a specially ventilated space which was only available between



Fig. 10: The flatbed





Fig. 11: A hand wound shape

Fig. 12: A digitally wound shape



Fig. 13: The fibre dispencer and resinbath

18:00 and 21:30. The resin started to become tacky after 20 to 30 minutes and in the area where the winders hand touched the resin the heat speeded up the curing process making the winding even more difficult. The whole process was physically intensive and the time limit made the process mentally intensive too.

The resulting models can be divided in two generations. The first is to determine the location of the fibre bundles and their effect on the overall shape. The second generation is used to optimize and preform structural analysis.



Fig. 14: The shaping parameters of the pillar

5.1.1. Parameters

The rough shape derives from multiple variables and the relation between them is modelled and investigated in a Grasshopper model. The parameters in this model are (fig 14):

- a. The distance between the top and bottom plane (H)
- b. The radii of the top and bottom circles (r_{top} and r_{bot})
- c. The amount of connection points on the circles (Pn), determines the amount of bundles
- d. The angle of the bundle determined by the shift of connection points when crossing between the top and bottom circle (Pnx)

The aim was to design an open structure consisting of bundles instead of creating a closed surface. Pn was kept constant during the experiments as variation could be achieved by selecting which points to use and which not. The Pn was 60 as it could be equally distributed over 3, 4, 5, and 6 sides.

5.1.2. First generation

The distinctive parameters of the first generation are the shape, size and number of the outer moulds and the points the bundle shifts on one mould element. The distance between the moulds (H) was primarily set to 33 cm. The models are described chronologically. The process started without a clear direction or scale.

Figure 15 shows the first model made with the flatbed winding configuration. First some polar windings are done, then by increasing the winding angle, some helical windings. Not all connection points (Pn) of the square and circular mould are used.

Figure 16 shows the model where all connection points are used in a systematic polar winding path. The moulds where not aligned properly and the shapes of the moulds minimized interaction between the different bundles.

Figure 17 shows smaller bundles used to form larger bundles in an open structure. The shape would not have aesthetic value derived specifically from its production technique.

Figure 18 shows a combination of systematic polar windings and secondary helical windings to compress the bundles for fibre


Fig. 15: The first model with random winding path and a circular and rectangular mould.



Fig. 16: The second mould with a consistant winding pattern and two rectangular based moulds.



Fig. 17: A structure consisting of non-interacting bundles was created.



Fig. 18: At the bottom hoopwindings are made for compaction and reinforcement.



Fig. 19: Two layers with different Pnx to form half a hyperboloid. Additional fibres are located on the opposite side to balance the model.



Fig. 20: Using three moulds to wind two hyperboloids with different Pnx. The bundles only interacted at the bottom half.

interaction. At the bottom the hyperboloid shape was used to add reinforcement with hoop windings. This same technique is used in the ICD/ITKE 2013 pavilion. Circular moulds seem to work best in terms of bundle interaction and aesthetic pattern.

Figure 19 shows a surface created by two winding angles. Like earlier models the shift in Pn between the two moulds (Pnx) of the first path is smaller than the last resulting in bend curves which are favourable for bundle interaction. Producing half a hyperboloid added difficulties but no clear advantage.

The model in figure 20 and 21 proceeds on the principle of different layers with increasing Pnx for enhancing interaction. By introducing a third mould a combination of two hyperboloids is created. It results in a double skin which is not interconnected.

In figure 22 the possibility of the additional moulds is investigated. The middle mould allows for two separate winding angles and might have functions such as bending moment constrained connecting of a girder-like roof structure. After making a digital model with multiple circular moulds different relative heights, Pnx and radii are investigated (fig 23 &24)

After some discussions the decision was made that the research should focus on the material and connections because if that could be solved future research could focus on more complex shapes. The following parameters were set by approximation:

Abbreviation	Parameter name	Ratio	
Н	Height		
r _{bot}	Bottom radius	1/4 H	
r top	Top radius	$2/3 r_{bot}$	
Pn	Connection points		
Pnx	Point shift	1/3 Pn	



Fig. 21: Detail of the double skinned hyperboloid which shows the difference in r and Pnx.



Fig. 22: Three moulds with a different Pnx.



Fig. 23: A Grasshopper output using three moulds with a different Pnx and r.



Fig. 24: A Grasshopper output with the largest mould in the middle of the shape.



Fig. 25: The first model with circular reinforcements and the hoop windings for the reinforcement of te bottom element.



Fig. 26: The more elaborate model uses two cobs to hold the circular reinforcements in place.

The bundles have to pass though all connection points before it reaches the starting point again. Therefore, not all values and combinations for Pn and Pnx could be used. The best way to prevent looping is to select a prime number as a value for Pn.

Figure 25 shows an important step in the design evolution; the addition of hoop windings. This will triangulate the structure and should result in more load bearing capacity and overall stiffness. The main problem is to hold the circular reinforcement at its location on the hyperboloid shape. An additional mould element is introduced on one side as a comb to prevent slipping. Due to imprecise manufacturing and lack of suitable material the model contains some flaws.

The model shows a first experiment for the connection detail. It consists of a wound ring to equally transfer the load to the mould when under compression. This design principle is further discussed in chapter 6 'The top and bottom details'.

The second model with the circular reinforcements (fig 26) was made with more precision and a second comb. It clearly shows the triangulated structure and that the pretension causes the bundles to bend due to their elasticity. The thickness of the nodes is increased as an extra bundle crosses. This behaviour is investigated in a full scale partial mock-up (fig 27).

The shape is resembles the towers by begin 20th century Russian engineer Vladimir Shukhov (fig 28). However, one of the differences being that the circular reinforcements does not exactly coincide at the intersection of the polar bundles. At the Kobe tower in Japan (1963) (fig 29), the connections meet at one point. The reason could not directly be identified nor was it further investigated.

The final model of the first generation is made of steel rods (fig 30) to exhibit the shape without the interior compressional structure. The model is not representative for the actual design in many ways but did not have the inner structure under compression which was required with the acrylic fibres.



Fig. 27: Detail of the layered intersections.



Fig. 28: The Shukofvtower in Novgorod, Russia is constructed in 1929 and has a hight of 128 m. It still stands as a monument.



Fig. 29: The 108 m high Kobe Tower is completed in 1963 and located in Kobe, Japan. It is still open for public.



Fig. 30: The steel wire model was the first without an inner structure.



Fig. 31: The top of the first composite model.

5.1.3. Second generation

The second generation physical models are made of composite capable of withstanding compressional forces. The models are therefore more representative for the actual column and require structural analysis as lines (trusses) become beams.

The process started with testing homemade manufacturing equipment and acquiring a basic skill level in working with composites. The experiments are discussed in chapter 8: 'Physical testing'. The static analysis is done using the Karamba plugin static analysis program and basic hand calculations.

The most dictating parameter is the fibre bundle thickness. The thickness is influenced by a broad variety of parameters in shape, material, forming technique and loads but determines the surface fill ratio at the waist of the pillar. Optimization requires extensive knowledge of each of the parameters which depend on physical tests and experiments. Collecting data for these parameters is dominant in the second generation models.

The first model made of glass fibre reinforced polymer (GFRP) had a height (H) of 70 cm, two circular moulds with a diameter of 30 cm at the bottom and 20 at the top (fig 31 &32). The amount of connection point (Pn) is 31 with a shift between the moulds (Pnx) of 10 per crossing. The path was fully completed two times resulting in four layers at the intersections, no circular reinforcements were made. The model was made to show at the P3 presentation and represented a four meter high column. During this presentation the decision was made to lower it so that a more open structure could be made (fig 33).

The following composite models are primarily made for the physical testing in a mechanical press. However, the preparation process gave additional insights in the whole structure and its details. To acquire reliable results at least five identical samples should be made and tested. As time was limited the decision was made to test only two types; with and without circular reinforcements, a total of ten models are made. The new design has a Pn of 19 with a Pnx of 6 and a height of 50 cm. Three layers of polar windings are made and the circular reinforcements consisted of six layers. Between the two connection elements eleven circular reinforcements are placed around the intersection points. These reinforcements required their own individual mould. The models are one to five in scale of a 2,80 meter high pillar. The impregnated fibres have an average section radius of 1,9 mm. The model is scaled linear for visual reasons. If the model should be scaled structurally it should have been nonlinear. This could have been done, however the model would look totally different as each of the parameters is scaled differently. For more detailed information on this content see chapter 7 'Structural analysis'.

During the winding process some complications were discovered in the winding path. Due to the stacking of layers with a



Fig. 32: Detail of the surface of the column.



Fig. 33: Different scales are tested by altering the size of the puppets. The new column was set at 2,5 m with the puppet in the middel.



Fig. 34: Type A of the testing models.



Fig. 35: Type B of the testing models with the circular reinforcements at every intersection.



Fig. 36: Detail of a type B test model. Due to the stacking of the layers not all fibres seem to interact within the bundles

certain thickness the stacked bundles did not interact well with each other (fig 36). This effect becomes larger as the tension on the fibres is increased and might result in unfavourable details. Two suggested ways to counteract this behaviour is by increasing the matrix volume fraction or reducing the thickness of each of the layers. With higher matrix volumes more material is required increasing the overall weight and waist fill percentage. Thinner layers will require a longer winding process which is limited by the pot-life. This effect requires further research including full scale testing.

5.2. Conclusion

The combination of the digital and physical models in an early stage of the design process was a powerful and rapid mean of investigation the coreless filament winding principles. This understanding allowed for more advanced modelling further in the design. Precise parameter values require more tests so still some decisions are made on approximations and assumptions. Together with the tests done it grants an insight to the possibility of winding this particular shape. More experiments with the composite materials and different winding paths would have been favourable. The technique exhibits aesthetic value deriving from its production technique.

Further research

Further research is recommended to include:

- a. Altering the shapes or planarity of the moulds
- b. The use of pigments in the matrix



6. The top and bottom details

The top and bottom elements are used as moulds and to equally distribute the forces on the fibres. As the mould determines the shape and a freedom in shapes is desired, the moulds production should allow for diversification. Low in weight is an additional ambition for the building process and material selection.

6.1. Principles

The principle of the section is to transfer the normal forces from the bundles to a force in the gravitational direction by the introduction of a circular reinforcement which has to expand in length as it is pushed down in global-Z direction (fig 37 &38). The load will then be transferred to a tension in the ring to result in the equilibrium of the forces in the Y and X directions. An extra piece is added to prevent the reinforcement from slipping off the element during winding and fix the connection of the composite bundles for a possible moment in the pillar.

For the top element a special design is made to transfer the load from the columns centre axis to the edges of the column. Additonally, a normal sphirical bearing can be mounted on top of the element (fig 39 &40). With the bridge deck acting as a point load in on the centre axis eccentricity is prevented.





Fig. 37: Bottom connection element of the first FRP model with the laser cut MDF sheet on top to hold the hoop windings in its place during winding. Sliding of the bundles should be prevented as it will damage the composite.

Fig. 38: The principle for the top and bottom connection. The force flows from the polar bundles and is prevented from sliding down by the circular reinforcement. At that location the vector is decomposed in a horizontal plane and in the global Z direction.



Fig. 39: Principle diagram of a PTFE spherical bearing. The support allows for rotation in all direction and the translation is constrained in the z-direction.



Fig. 40: 3D image of a spherical bearing which allows for translation in only one direction of the horizontal plane.

6.2. Details

The element is made from water-cut steel sheets as the material and production technique is broadly available. Multiple sections of a circle are welded to form a cone. On the small radius a steel ring is welded for stability and to hold the circular reinforcement. At the bottom element an additional circle is welded to connect the element to the base. The top element to transfer the load is also made from steel sheets and on top there is a PTFE spherical bearing which is constrained in the Z-direction. Between the top two elements additional shock absorption material is placed. Water-cut sheets have edges which can cut the fibres during winding. Therefore either short steel tubes or specifically made elements of aluminium or a cast polymer are bolted on the cone.

6.3. Example

During the physical tests one of the models seem to have had a flaw in the placement of the moulds. This resulted in the reinforcement not being fully pressed onto the element (fig 41 &42). The effect was that the wooden cone was able to move towards the inside of the hyperboloid. The diverging shape was stopped by the circular reinforcement exhibiting the expected behaviour of the element.



Fig. 41: The initial connection at the top of one of the models; the cricular reinforcement is fully pressed onto the element.



Fig. 42: The top connection after the physical compression test; the wooden shape shifted inwards but was restrained by the circular FRP reinforcement. The result is a gab at the connectionpoints.



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6.4. Conclusion

The manufacturing technique using the cut steel sheets and bolted on connectors is labour-intensive but conventional and therefore reliable. Structural analysis should substantiate the plausibility of the detail and the required thickness of the steel sheets. For these elements the idea of expressing the production technique is applied. Having the elements act as a mould it reduces the additional labour of extracting and waxing, it however, requires to make a new element for each of the pillars.

Further research

- a. Using automated techniques such as 3d printing
- b. The influence of the fibres sliding over the surface
- c. The minimum angle for the principles to work in practice



7. Structural analysis

The structural analysis chapter is divided in two sections. The first discusses the input values, the equations and their correlations. The second includes the output, derived from hand and computational calculations.

7.1. Constraints

To investigate the principle of the filament wound pillar the shape is simplified and follows two basic rules:

- a. The shape is a basic hyperboloid of revolution with parallel top and bottom plane
- b. A maximum surface openness should be achieved with a maximum waist fill of 33%

7.2. **Loads**

The loads of the bridge should act on the central axis of the column to prevent eccentricity thus allow for equal distribution through the pillar's section area. The loads acting on the pillar are the live and dead load of the bridge deck (Fz) and the load of the wind (Fy). Additionally a force in the direction of the bridge deck (Fx) might appear by a braking vehicle and is ideally transferred to the bridge heads. This load is in this symmetric shape the same as Fy, but should be taken into account in future non symmetrical designs.

Making the connection to the bridge deck pinned prevents bending moments and torsional forces from occurring in the column. These forces should be dealt with outside the column (i.e two pillars next to each other, stiff or bended deck). The base of the pillar has enough width to take the wind load on the bridge deck but is kept to a minimum by suggesting an open structure.

The design values are:

Name	Value	Argumentation
Distance between pillars	10 m	
Width of bridge deck	3,5 m	2 bike lane + 1 pedestrian
Live load	$5 \mathrm{kN/m^2}$	EN1991-2 NB
Dead load bridge deck	2,5 kN/m ¹	FRP monocoque
Dead load pillar	3 kN	Approximation
Safety factors (ULS)	DW = 1,2 LL = 1,5	NEN-EN1990 Fx
Total dead load	32,5 kN	
Total live load	262,5 kN	Z
Total load (Fz)	295 kN	$\begin{pmatrix} F_z \end{pmatrix}$ χ
Wind load area	10 m ²	Approximation
Wind load	1 kN/m²	Dutch standard
Total wind load (Fy)	10 kN	

7.3. Surface or wireframe

Throughout the process there is a discussion on whether to approach the pillar as a surface with holes or as a wireframe. The major difference is that the surface would be double curved and the wireframe consists of straight elements only. The calculations for both approaches are quite different so determining the structural behaviour is crucial. The difficulty is finding the point where one becomes the other when increasing the waist section fill percentage.





Fig. 45: The surface approach: When pressure is applied on the hyperbolic curve it tends to deform in the curves direction. This force is largest where the curvature is smallest.

Fig. 46: The wireframe approach: When pressure is applied on the staticaly indeterminate straight line it tends to deform as a sinusoid.

7.3.1. Surface approach

The surface approach is similar to that used for an industrial cooling tower. In the vertical section, the load passes through a hyperbolic curve resulting in a normal force (N ϕ) and a force perpendicular to the surface (fig 45). This resulting force has to be dealt with in the circle resulting in a hoop stress (N θ) in the XY section. At waist (r2 or a) the hoop stress is highest as the radius of the curvature of the hyperbola (r1) at this point is smallest. The relation between N θ and N ϕ is described by Haas (1967) as:

$$N_{\theta} = -N_{\varphi} \frac{a}{r1}$$

Nφ= Normal forceNθ= Hoop stressa= radius of pillar at waistr1= radius of hyperbola at waist

The force $N\phi$ is equally distributed over the full section XY line which is cut at the intersections of the bundles. To find the load on each bundle the force has to be distributed over two bundles in the angle a.

$$N_{\eta} = \frac{0.5 \ N_{\varphi a}}{\cos(\alpha)}$$

 $N\eta$ is then used as the critical force in the buckling calculation.

In the design of the pillar the ratio of N θ and N ϕ is approximately 1 to 8 at waist. This load cannot be resisted by the stiffness of the bundles as eccentricity will drastically decrease the maximum allowed force for buckling in the bundles. Additional material is thus required in the direction of the force. The proposed solution is to introduce circular reinforcement at the intersections. This will triangulate the surface. To prevent bending moments to develop these reinforcements should coincide with the existing intersections of the polar bundles.

7.3.2. Wireframe approach

The other method is calculating the equilibrium of each connection as a static indeterminate structure (fig 46). The stiffness will derive completely from the bending stiffness of the bundles. This means assuming all bundles to be perfectly straight and non-eccentrically loaded. In this case no circular reinforcement is needed for the hoop stress. They could be applied for stability against buckling where the bundles are longest.

7.4. Buckling and its parameters

Buckling is assumed to be the primary mean of failure as maximum slenderness is desired. The equation for buckling is:

$$F = \frac{\pi^2 EI}{(KL)^2}$$

F	= Critical force at which the bundles collapse
E	= Elastic modulus
Ι	= Moment of inertia
К	= Effective length factor
L	= Length of the beam

The equation shows the most ideal situation for eccentricity and constant material properties. Both can be influenced during use by external influence like weathering and impacts. To estimate the realistic maximum load an additional safety factor is introduced to lower the design critical force.

To express the influence of each parameter on the critical force the following statements can be made:

2 x E	= F x 2
2 x I	= F x 2
2 x L	= F/4
2 x K	= F/4

Elastic modulus

To indicate the material parameters the Granta CES Edupack 2014 database is consulted. CES is the database which is supplied at the architecture faculty of the Delft University of Technology (DUT) and gives an indication of the 'normal' extremes of material properties.

The following table shows the values for a glass fibre in polyester pultruded rod with a different fibre weight fraction.

Fibre weight fraction	40 - 45	65 - 75	%
Density	1660 – 1940	1900 - 2100	Kg/m ³
Elastic modules	17 – 18	35 - 45	GPa
Elastic strength	207 – 227	690 - 828	MPa
Compressive modulus	17 – 21	35 - 45	GPa
Compressive strength	114 - 138	414 - 483	MPa
Flexural modulus	11	41 - 45	GPa
Flexural strength	207 - 227	690 - 828	MPa

The material properties are those of a pultruded rod and might be too optimistic as that process is more controlled than the core-less filament winding techniques used for the pillar. Clearly visible is the influence of a high fibre volume fraction to its moduli. In the case of the pillar the only required modulus for buckling is the elastic modulus. The yield strength to be used is the compressive strength.

According to the rule of mixtures the elastic modulus can be determined by the weighted mean of both composite materials (Campbell, 2010). The equation exhibits the following relation:

$$E_c = V_f \times E_f + (1 - V_f) \times E_m$$

Ec =	Elastic	modulus	of	the	composite
------	---------	---------	----	-----	-----------

Ef = Elastic modulus of the fibres

Em = Elastic modulus of the matrix

Vf = Fibre volume fraction

1 - Vf = Matrix volume fraction

To determine the fibre volume fraction the fibre weight fraction can be used as described in the following equation:

$$V_f = \frac{\frac{W_f}{\rho_f}}{\left(\frac{W_f}{\rho_f} + \frac{1 - W_f}{\rho_m}\right)}$$

 V_{f} = Fibre volume fraction

 W_{f} = Fibre weight fraction

 ρ_f = Fibre density

 ρ_m = Matrix density

To validate the equations or find a reduction factor between the theoretical elastic modules and that derived from testing the values for CES are calculated. For the high volume fraction the elastic moduli are corresponding. For the low volume fraction this is not the case. The difference is a factor 0,75 in the favour of the theoretical modulus. Possible argumentation is that the values in CES are not derived by testing for the high volume fraction composite but are calculated thus actually is the theoretical modulus. Other reasons might be that a high fibre fraction is often used for advanced composites so has a higher quality when it comes to voids in the matrix, fibre matrix bonding and materials used. No specifics on the used resin are given besides it being polyester.

Extra caution should be used when selecting the elastic modulus for calculating fibre reinforced polymer structures using unconventional techniques. To find the actual elastic modulus doing tests seems essential.

Moment of inertia

The section of the rods should be strong enough to deal with the compressional force and stiff enough to prevent buckling. As the shape is wound with a constant thickness the rod on which the highest force is applied dictates the overall section. The equation for the moment of inertia (I) depends on the section of the profile. For a rectangular profile the equation is as follows:

$$I = \frac{1}{12} \times w \times h^3$$

w = width of the bundle

h = height of the bundle

Therefore, the following statements on the influence within the buckling equation can be added:

2	Х	w			=	F	х	2
2	х	h			=	F	х	8

The distinction between height and width of a profile is determined by the direction of the force. When loaded with a noneccentric normal force an unconstrained bundle will bend in its weakest direction (w).

For the columns without the circular reinforcements (type A) the nodes are more likely to rotate in the direction perpendicular to the columns rotational axis. To enhance the strength additional material should be added so that the w equals h³ to diminish a weakest axis. For the column with the circular reinforcements (type B) additional stiffness is added to the nodes in all directions. Especially since the horizontal bundles are shorter than the vertical. The weakest axis for these columns remains unclear and should be researched utilizing physicals tests.

After the small scale experiments rectangular sections seems to be unlikely as the section profiles became more circular. For a circular profile the equation is as follows:

$$I = \frac{\pi}{4} \times r^4$$

r = radius of the bundle section

Therefore, the following statements can be added:

When A is equal: $I_{\mbox{\tiny circular}}$ is 95% of $I_{\mbox{\tiny square}}$

When I is equal: The height of bundle section is 3% increased for circular profile

This shows that the difference between a circular or a square section is limited. The manufacturing process and the used size of roving will determine the actual shape. Assumed is a shape somewhere in between a circle and a rectangle.

The section profile is limited by three factors:

- a. The influence of the fibre width on the fill of the pillars waist section
- b. The maximum allowed thickness for complete cure within an acceptable time
- c. The strand and stacking thickness during the winding process

The first is determined by keeping the summation of all bundle widths under the desired waist section fill of 33% for aesthetical reasons. The second is a material property so optimized by the material selection up to a certain value. The last is very flexible due to the diversity of available materials and winding possibilities.

The effective length factor

The effective length factor (K) derives from the boundary conditions. Theoretically they are:

Constrains combination	Effective length factor (K)
Fixed-fixed	0,5
Fixed-pinned	0,699
Pinned-pinned	1,0
Fixed-unconstrained	2,0

The interactions themselves tend to seem fixed-fixed as they are made in a wet on wet resin layup process. However, as the points are floating on a two dimensional grid in a three dimensional space rotation of the whole nodes might be possible. The structure is statically indeterminate which in this case means that the bending moment in the connections will be taken by the stiffness of the next segment of the bundle. Each node consists of four different directions for the type A column and six for the type B column from which the bundles intersect. The actual value for K can be found somewhere between 0,5 and 1,0. For the calculations the nodes are pinned-pinned as safety factor and a worst case scenario.

The bundle length

The bundle length (L) is the distance between the intersections of the fibre bundles. This distance is determined by the height and radii of the top and bottom circles of the hyperboloid, the amount of connection points thus the amount of bundles and the ratio between Pn and Pnx. Theoretically this point is found at where the centrelines of two bundles coincide.

Increasing the amount of bundles will reduce the distance between the intersections, however, this will fill the section at the waist of the pillar. Also, when L becomes shorter its required I will be less resulting in thinner profiles. This can be interesting as L/2 means an increase of Fx4 while 2x(w) results in a Fx2 as described earlier. However, reducing the profile thickness is limited in practice.

L is shortest when the ratio between the amount of connections (Pn) and the shift between the upper and lower circle (Pnx) is around 25%. Using the Grasshopper software gives the following values:

Pn	Pnx	Ratio
31	8	0,26
35	9	0,26
41	12	0,29
45	11	0,24
51	13	0,25
55	14	0,25





Fig. 47: Grasshopper output of a Pn to Pnx ratio of 26% Fig. 48: Grasshopper of

Fig. 48: Grasshopper output of a Pn to Pnx ratio of 32%

Pn was set and Pnx was then optimized to find the lowest value for L. The values are biased as for some combinations of Pn and Pnx the looped before all connection points were reached.

The chosen ratio however is 0,33 for aesthetical reasons (fig 47 &48).

7.5. Strength

The strength is determined by the maximum level of stress a material can handle. Therefore the maximum stress should not exceed the materials yield stress. Stress is the amount of force on a certain surface thus:

$$\sigma = \frac{F}{A}$$

σ	= Stress
F	= Force
A	= Section surface area

The bundle section required to prevent buckling seems to be six times higher in the hand calculations. For the actual column material samples should be made and tested prior to the final design process.

7.6. Structural requirements

For the column to achieve its maximum load bearing capacity three aspects are critical; the compaction of the composite, the straightness of the bundles and the strength of the connections. Normal composite forming uses a mould on which the material is compressed during curing. This compression is required to remove air pockets and increase the bonding quality and durability. For coreless filament winding a solution needs to be invented. The straightness of the bundles is highly increases the critical force for buckling as it prevents eccentricity. Finally, the strength of the connections determine the effective length factor (K) in the buckling equation and when it is very poor the bundles might not act together increasing the working length of the bundle (L).



Fig. 49: The stacking effect of the bundles

The first suggestion was to apply a tension in the whole column by increasing the distance between the top and bottom elements after completing the winding process but before curing. This will increase the straightness and the thickness of the bundles might result in a force perpendicular to the bundles to enhance material compaction and the connection strength.

Other investigations included wrapping the column in a material or with a technique that allows applying a force perpendicular to the bundles. This could be a foil that shrinks when heated or a hose in hoop winding direction filled with water. These additional process steps are unfavourable as they increase labour.

The final solution is to compress the material with the circular reinforcements on an additional mould. Each winding path should therefore end in a sequence of circular reinforcements. Calculations show that some reinforcements is forced inwards and thus are compressed while others will be tensioned. Calculations show that the required bundle thickness of the hoop windings will be less than the polar windings. The centrelines should coincide to prevent eccentricity in the nodes. The final layer for compaction might therefore not interact with the structural hoop winding layer.

7.7. Calculations

First the in- and output data derived from the Grasshopper model and used for the calculations are shown. Then the hand calculations are reviewed. These include the calculations according the surface and the wireframe described earlier. Then the calculations made using Karamba are discussed.

Geometrical input	Abbreviation	Value	Unit
Pillar height	Н	2800	mm
Bottom radius	r _{bot}	700	mm
Top radius	rtop	420	mm
Connection points	Pn	19	
Point shift per crossing	Pnx	6	
Fillet connection points	r _{fillet}	25	mm
Thickness bottom element	t _{bot}	230	mm
Thickness top element	t_{top}	160	mm

First a summary of the input and output data is given:



Fig. 50: 3D, elevation and top view output of the Grasshopper model for type A.



Fig. 51: 3D, elevation and top view output of the Grasshopper model for type B.

Geometrical output	Abbreviation	Value	Unit
Intersections		418	
Circular reinforcement		11	levels in vertical direction
Max length bundle	L	409	mm
Radius at waist	a or r _{2,w}	283	mm
Radius of curvature at waist	$\Gamma_{1,W}$	2462	mm
Radius at lowest intersection	r _{2,low}	515	mm
Radius of curvature at lowest	$\mathbf{r}_{1,\text{low}}$	2994	mm
intersection			
Angle at intersection	α	25	degrees
Total polar length type A		110	m per layer
Total length type B		126	m per layer

For this geometry the following load and material properties are applied:

Parameter	Abbreviation	Value	Unit
Total load on column	Fz	292	kN
Elastic modulus	Е	17500	MPa or N/mm ²
Moment of Inertia	Ι	(none)	mm ⁴
Effective length factor	K	1,0	
Compressive strength	σ	114	MPa or N/mm ²
Density	ρ	1800	kg/m ³

7.7.1. Hand calculations

In the first hand calculations a moment of inertia is calculated for perfect conditions. A radius is calculated which forms a bundle with at least that I. A circular profile is chosen as has a low surface to I ratio (it is an ineffective profile section).

The highest load in the circular reinforcement is assumed at waist, so the thickness at that reinforcement is given. The highest probability for buckling is at the longest bundles. Additionally the profile for the lowest circular reinforcement is given as it is the longest bundle in hoop direction.

Pillar section	Νη	Νθ	$\mathbf{I}_{\min, polar}$	r _{bundle}	I _{min,hoop}	r _{bundle}
	[N]	[N]	[mm4]	[mm]	[mm4]	[mm]
At waist	7871	-5342	-	-	491	5
Lowest	7871	-6954	7402	9	491	5
intersection						

Even though the force in the circular reinforcement is different for the two hoop windings, due to buckling, the required section is approximately equal. The weight of the composite material is estimated around 70 kg.





Fig. 52: The total load was divided over the 38 bundles to result in a force of 7684 N per bundle in global z-direction.

Fig. 53: The boundery conditions dictate constrained bending moments (purple) in all directions and a constrained translation (green) in the X and Y directions is all supports. The bottom support also has a constrained translation in z direction.

7.7.2. Karamba

For the Karamba calculations the whole model has to be scattered between the intersections. This results in 456 elements for the polar windings and 209 elements for the circular reinforcements. The polar windings start after the bottom or top connection elements as they are assumed to constrain the bending moments (M) and translation (T) in X and Y direction. The bottom elements are fixed to the ground thus translation in Z direction is impossible. The force is applied on all the top nodes. This force is 292 kN divided by 38 beam elements: 7684 N in the Z direction (fig 52 &53)

The following boundary conditions are set:

	Tx	Ту	Tz	Mx	Му	Mz
Bottom connection	х	х	х	х	х	х
Top connection	х	х		х	х	х
Intersections				Х	Х	Х

Constraints had to be set for the intersections because the model is build up from small elements. This joint stiffness is determined by the rotational stiffness (k) given in kNM/rad. For these calculations the stiffness is fully constrained as the beams are formed over the full length of the pillar and thus act as one element. Further research on the rotational stiffness could prove necessary to give more realistic results.





Fig. 54: The deformed type A model; the total displacement is less then of the type B model as it has a higher profile thickness. The model becomes thinner near the waist.

Fig. 55: The deformed type B model; the triangulated surface had a even deformation across the whole model.

Туре А	Nη,max	Compression [c]	Profile diameter	Profile area
	[N]	Tension [t]	[mm]	[mm²]
Polar	8115	с	26	531

The weight of the composite material for type A is 95 kg.

For type B the first calculations are done with all of the 11 circular reinforcements. The reinforcements are calculated for buckling and yield using the Galapagos optimization plug-in.

Туре В	Nη,max	Compression [c]	Profile diameter	Profile area
	[N]	Tension [t]	[mm]	[mm ²]
Polar	8121	с	18	254
Circle 1	27	с	13	133
Circle 2	30	с	8	50
Circle 3	64	t	4	13
Circle 4	60	с	2	3
Circle 5	21	с	1	1
Circle 6	9	с	1	1
Circle 7	30	с	11	95
Circle 8	1	с	6	28
Circle 9	11	с	0	0
Circle 10	88	с	11	95
Circle 11	2888	t	7	38





Fig. 56: After the reinforcement optimization process only six of the initial eleven remained.

Fig. 57: The deformation is largest where there is no reinforcement. The image is strongly exaggerated but clearly shows the direction of the deformation.

The normal force at Circle 11 requires further investigation as it deviates too much from the other circles. Also a more equally distributed profile area would be assumed. This has probably to do with the Galapagos optimization. Further research should be done to counteract these flaws.

The weight of the composite material is 71 kg for type B. The difference in bundle area seems too large for a realistic winding path as all bundles are made with one bundle size. By reducing the thickness of the band the winding path will become too long. The amount of circular reinforcements can be reduced to six when optimization is done:

Туре В	Nη,max	Compression [c]	Profile diameter	Profile area
Optimized	[N]	Tension [t]	[mm]	[mm ²]
Polar	8181	с	18	254
Circle 1	4689	с	11	121
Circle 2	297	t	12	144
Circle 3	21	t	20	400
Circle 6	1488	с	14	196
Circle 7	2236	t	14	196
Circle 8	819	с	17	227

This reduces weight to 50 kg. The circular profiles are thicker but the required mould and winding path are less complex. The result are biased by the fact that Karamba works with isotropic materials only.

The value for circle 3 seems incorrect as it has a relatively small normal force, but by far the thickest profile. The cause could not be determined. Extended knowledge of the software is required to find what and where the problem is.

7.8. Discussion

To compare the results of the hand calculations with the digital results full understanding of the underlying processes of Karamba is required. It remains unclear to what extend the structure behaves like a surface or a wire frame. The calculations by Karamba resemble the hand calculations in profile thickness but the results could not be validated. What both calculations do state is that buckling is in all cases the primary cause of failure.

When regarding the requirement of a maximum 33% fill at waist as determined during the shaping process the following statements can be made. The circumference at waist is 1778 mm:

According to the hand calculations the bundle thickness is 18 mm resulting in a fill of 684 mm or 38%. Karamba give a thickness for type A of 26 mm filling the waist for 988 mm or 56%. For type B with a bundle thickness of 18 mm the fill corresponds with the hand calculations. None of the shapes seem to meet the fill requirement.

Suggestions are made in two directions:

The first is reducing the load on the bundles. This can be done externally by decreasing the distance between the columns or narrowing the bridge deck. Or this could be done by reducing the radii of the bottom and top circle. The angle in which the bundles are loaded will be less and the distance between the intersections will be smaller. This is an aesthetic trade-off between curvature and openness. Also, when the angle of the top and bottom elements is too low the principle of the local reinforcement rings might not work (chapter 6: The top and bottom details). What is less an option than it seems is changing the Pn and Pnx. Other values seem to loop before all connectors are used as mentioned in chapter 5.1.1: Parameters.

The second solution might be found internally by increasing the elastic modulus. As the pillars are low in weight more expensive materials can be used without drastically adding to the overall cost. As suggested earlier this could be vinyl ester or epoxy combined with stronger S-glass or carbon fibres. This only works when the production process creates well interacting intersections and overall composite.

A final note has to be stated concerning the estimated winding time. The roving size and fibre volume fraction will determine the minimal thickness of the bundles. A 9600 (4 x 2400) TEX band with a fibre volume fraction of 30 to 35 will have a 10 mm² profile section area. This will still require at least 26 polar winding sequences for type B. For type A the band might be bigger, however, the result of too thick bundles might be a distance between layers at the intersections. Full scale testing is required to determine the ideal band thickness. The winding path will consist of multiple kilometres which is an important aspect in selecting the winding configuration and material.

Further process

Further process is recommended for:

- a. Physical testing to specifically determine if it is a surface or wireframe
- b. Further elaborated and validated digital analysis, specifically on the intersections
- c. The influence of a wind load

8. Physical testing

This chapter describes the physical tests conducted during the research. The first part consists of the small scale tests performed before the P3 presentation on April 2nd. The second part includes the tests performed after the P3 presentation. The material and the technique do not have the quality of commercial grade products. Nevertheless, they pointed out the weaknesses in the models. These tests give insight in the structural behaviour and helps understand the manufacturing process and the effect of the different winding paths.

8.1. Small scale tests

The composite and process materials are ordered at carbonwinkel.nl. The mould materials are bought at the architecture faculty or retrieved from the garbage containers. Three layup processes are tested: Impregnating the whole fibre bundle in a bag, winding the dry fibres on the mould and using a brush to apply the resin afterwards. The third is using a resin bath and applying the impregnated fibres to the mould.

Working with polyester was prohibited indoors so all testing was done outdoors. Therefore the temperature during layup was between 10 and 15 °C. Curing was done inside with a constant temperature of 18 to 20 °C. The digital scales to measure the weight with a precision of one gram.

Some destructive testing is done by hand to investigate yield behaviour. Due to the low quantity of the samples the tests don't have academic value. However, they helped to understand the behaviour of the material during and after manufacturing. Testing for material properties is not done as the materials are chosen for availability and price. No information was given on the quality of the fibres and the sizing. According to assistant Professor S. Koussios the quality, including the bonding of matrix to fibre, can differ between the producers.

There were three days of testing; March 25th to 27th. The UP was only allowed in the faculty's paint room after it was closed; this meant that experiments could only be done between approximately 16:00 and 17:15. The days consisted of a first analysis of the experiments of the day before and making the moulds and resin bath. The analysis was done using the scales and a visual check for air pockets and wet-out constancy. Due to the translucent matrix and mutual refraction visual inspection was possible.

8.1.1. Materials

- a. Matrix: UP-laminating resin Palatal U 269 TV-01V: pot life of 20 minutes
- b. Fibre: E-Glass fibres with silane sizing (R&G)
- c. Initiator: MEKP 2% of UP resin
- d. Release agent: Partall Paste #2
- e. MDF board with multiple thicknesses



Fig. 58: 'Hairy' fibre bundles

8.1.2. Test day one

The goal was to get a first understanding of the fibres and resin. Two techniques were tried; the first was to put all fibres (100 m) in a bag and fill it with resin. Then pull out the impregnated fibres directly out of the bag and onto the mould. The second technique was to dry-wind the fibres and apply the resin by brush afterwards.

For the first test the cardboard roll was removed from the fibre bundle, this led to complete entanglement of the different bundles, rendering it completely useless. The brush experiment gave high control but was time consuming. Additionally, the brushstrokes made the fibre bundles to become 'hairy' (fig 58).

After the different layups the rest material was monitored to understand the pot life of the material. This was done by looking at the viscosity and the way it became lumpy.

The findings are that the fibres should stay as a bobbin to be workable, the fibres become 'hairy' when stroked, the impregnated bundles tend to get a circular section and the resin becomes lumpy after 20 minutes but still has an acceptable low viscosity.

Results

Four straight bundles are made with a brush and five by winding the impregnated fibre bundles. Each bundle consists of one roving. The brushed bundles were acceptable in surface and little air pockets could be discovered with the naked eye. The preimpregnated bundles are very hairy and inconsistent in fibre volume fraction.

8.1.3. Test day two

The goal was to test the resin bath prototype, fibre dispenser, investigate the effect of layed-up intersections and compare the brushed bundles with those of from the resin bath. Four resembling MDF moulds are made for the intersections sections, two for the brushing method and two for pre-impregnated. All four have bundles consisting of two layers, resulting in a four layers stacked node (fig 59).

The fibre dispenser worked well. The resin bath was accidently filled over its limit, there was no nipping point and the friction was too high. All winding and brushing was done within the 20 pot-life minutes.



Fig. 59: The wooden mould with the composite sample

Prior to winding the weight of the wooden moulds was determined, then, for the brushed samples, the fibres. Thirdly the whole mould and all material were weighted and the difference determined. Finally the weight of the specimen with an arm length of 195 x 200 mm was measured to approximate the fibre weight fraction.

Results

The four intersections came out as expected. The following information was gathered (note that the precision of the scales has major influence on the results):

Samples	Total weight	Matrix weight	Fibre weight	Additional info
	[g]	[g]	fraction	
Brushed 1	4	2	30% - 60%	Large voids and high level of 'hair'
Brushed 2	4	2	30% - 60%	Less voids but a clear twist in the bundles.
Resin bath 1	6	4	25% - 45%	High quantity of dripping and small voids, also 'hairy'
Resin bath 2	6	4	25% - 45%	less hairy but still small voids

Destructive tests

The goal of the test is to observe yield behaviour of the intersections. The first test is done by an in-plane transverse force (like a clock), the second by an out-of-plane (like a hyperbolic paraboloid).

The first brushed specimen was tested with a transversal in-plane force. Bending in the fibre bundles creates a torsional deformation which causes the connection to delaminate. This occurs after approximately 45° rotation deformation.



Fig. 60: The brushed sample 1 after the test; the connection was delaminated



Fig. 61: Different moulds were used for different samples on day three

The resin bath 1 sample was tested with an out-of-plane transversal force (fig 60). The inner layers seems to be the first to fail, this might be caused as the load in the outer layers is in the direction of the fibres whereas in the inner layers the forces are perpendicular to the fibres.

8.1.4. Test day three

The goal for the third day was to test thicker profiles, the new resin bath and a polyester-acrylic fibre composite (fig 61). The bundles from test day two are slender which makes them flexible, this flexibility forced the bundles to delaminate. To experience the strength of the material and prevent such deformation a thicker profile was made using four or five layer bundles. To test the composite without the stiffness of the fibres a special sample was made with the acrylic fibres used in earlier models.

Results

All samples came out as expected.

Sample	Layers	Weight	Test result
		[g]	
Cross 1	5	12	Strong, sudden crack but
			not completely through,
			remains strong and stiff
Cross 2	4	10	"
Acrylic	4 yarns	-	Very weak, fibres break
			clean of in the matrix

8.1.5. Conclusion

The experiments showed the threads in the winding process. For the tests more sample of the same type should be made to reduce the influence of flaws. More planning on the process will be done for the further tests.

8.2. Large scale

The large scale testing was done to investigate the failure behaviour of the structure. Using the buckling equation as a theoretical guideline the difference in values from digital databases and the properties of the materials and shapes constructed using this filament winding method can be analysed. The buckling equation is chosen as buckling is assumed to be the primary cause of failure. A diversity of tests is executed to find an indication of the equations parameters.

The models are categorized in type A for the models made with only polar windings and type B with a combination of polar windings and hoop winding as circular reinforcement. Both models have top and bottom reinforcements at the supports.

8.2.1. Used materials and equipment

New materials had to be ordered as 10 models needed to be made. Also, the winding time needed to be increased to be able to wind multiple samples one after the other.

- a. Matrix: UP-laminating resin Crystic 2-446PA: pot life of 30 minutes at 20 °C
- b. Fibre: Jushi E6 386T E-Glass fibres with silane sizing
- c. Initiator: MEKP 2% of UP resin
- d. Retardant: NLC 10; 0,1 to 0,2 % of UP resin
- e. Release agent: Partall Paste#2
- f. MDF board with multiple thicknesses

For the small batches of resin used for winding the samples measuring 0,2 ml of retardant would be unpractical. Therefore the NLC 10 was diluted ten times with styrene before added to the UP resin.

8.2.2. The samples

The configuration is more elaborated than that used for the first FRP model. The roving is extracted directly from the bobbin and the new resin bath allows for more resin to prevent the winding process to be paused for a refill. A pay-out eye was created to assist the placing process and for a more consistent fibre volume fraction. To determine the weight of the individual composite materials the top and bottom elements are weighted prior to the winding process. Afterwards, the full weight of the model is measured and the weight of the moulds is extracted.

Two mould types are created. Again, a part of the mould would be left inside to transfer the loads at the top and bottom for all 10 of the models. To streamline the manufacturing process the connection points and the reinforcement holder are laser cut. The central piece was sawed and sanded by hand to the angles 14° and 17°. The mould (fig 62 &63) for the circular reinforcements had to be extracted after curing. Due to the high level of manual labour the moulds differ slightly from each other.

The models have a height of 50 cm, a bottom circle radius of 13 cm, a top circle radius of 8 cm and at waist the radius is just below 6 cm. Pn is 19 and Pnx 6, in the vertical axis the bundles intersect 11 times. The total path for type A is wound three times. Type B has three layers of polar windings and six for the circular reinforcements. For both models the top and bottom reinforcement consists of three to four layers of roving and is only applied when all other layers are placed.

The weight of the wooden elements is around 350 g for the bottom piece and 190 g for the top. The fibres used are 2400 TEX with a density of 2600 kg/m3 and an elastic modulus of 81,0 GPa. The matrix has a density of 1200 kg/m3 and an elastic modulus of 3,8 GPa. The elastic modulus is given by the material supplier and matches the values by the CES software and other sources. To



Fig. 62: The mould for the type B had 11 additional mould to construct the circular reinforcements with. The angle and location of these moulds derived from the Grasshopper and was tested and adjusted with a dry acrylic fibre layer. The theoretical location of the intersection points slightly differed from those in practice.



Fig. 63: To make extraction possible the mould was made of 23 semi-cirles which were tensioned with elastics on a cardboard tube. For the winding path nails were used to bend the bundles and hold them at their location. The intersections of the polar bundles were precisely between the black markings on the moulds. determine the theoretical stiffness of the composite the rule of mixtures is applied, therefore the fibre volume fraction is required. The following equation is used for the fibre volume fraction:

$$V_f = \frac{\frac{W_f}{\rho_f}}{\left(\frac{W_f}{\rho_f} + \frac{1 - W_f}{\rho_m}\right)}$$

- V_{f} = Fibre volume fraction
- W_{f} = Fibre weight fraction

 ρ_f = Fibre density

 ρ_m = Matrix density

The rule of mixtures to calculate the theoretical elastic modulus is:

$$E_c = V_f \times E_f + (1 - V_f) \times E_m$$

 E_{c} = Elastic modulus of the composite

 E_{f} = Elastic modulus of the fibres

 E_m = Elastic modulus of the matrix

 V_{f} = Fibre volume fraction

Type A is wound using 64 m of fibre resulting in a weight of 153 g. The models contain around 305 g of composite material from which approximately 150 g is matrix. The fibre weight fraction is thus around 51% which indicates a fibre volume fraction of 32%. The theoretical elastic modulus is then 28,2 GPa.

Type B has 77 m of fibre with a weight of 185 g. The total weight of the composite is 410 g thus contains around 220 g of matrix. The result would be a fibre weight fraction of 45% and a fibre volume fraction of 27%. The theoretical elastic modulus is 25,0 GPa.

The theoretical elastic modulus does not correspond to the values from the CES Software. To find the elastic modulus additional tests are required. These tests are done by pulling a sample single roving bundle and find the stress to strain ratio. 27



Fig. 64: 27 single strand composite bundles were made to test for the elasticity modulus. Only five that had the most constant and comparible thickness were actualy tested.
samples with a length of 33 cm were made during the manufacturing of the other models (fig 64). They have a circular profile with a diameter of 1,8 to 1,9 mm. To calculate the elastic modulus the following equation is used:

$$E = \frac{\sigma}{\varepsilon} = \frac{\frac{F}{A}}{\frac{\Delta L}{L}}$$

- E = Elastic modulus
- σ = Stress
- ε = Strain
- F = Force
- A = Section surface area
- ΔL = Difference in length when loaded
- L = Initial length

Winding the reinforced column is done by first applying a single layer of polar windings, then one sequence of circular reinforcements, followed by two layers of polar windings and concluding in a second sequence of circular windings. The idea behind this order is that the first layer of circular windings is well compacted in the whole structure and the last layer of circular windings is especially to compact the intersection points. When more layers are applied the winding order will become a crucial aspect for the strength of the structure when not stacked in the right order delamination might occur. The circular winding sequence consist of two layers each time they are wound. This was the necessary to form complete circles as the connection points were place parallel to the rotational axis of the mould. The surface area between the two bundles would be too small to form a stiff circle (fig 66).

The circular reinforcements should precisely join the intersections of the polar windings. In the models this is not the case due to the errors in the mould and its alignment. The result is that the surface is not triangulated but divided in small triangles and



Fig. 65: The windings between the circular reinforcements are intentionally left thin to keep the bundles flexible to prevent structural interference.



Fig. 66: To wind the circular reinforcements at least two layers had to be made to form a full circle

diamond shapes.

During the winding process some errors are made that might influence the structural capacity of the whole column. These flaws include a bundle that had got stuck behind a circular reinforcement connection point and become crooked (fig 67). Another error assumed to affect all models was caused by the winding principle. During the winding process a constant tension had to be applied. This was done at the pay-out eye using friction by squeezing it. This caused resin to be nipped off unintentionally and uncontrolled. The result is an inconsistent composite material especially at the area a couple of cm after the connection points. Furthermore, a repeating inconsistency was caused by fixing minor errors during the winding process (fig 68). This caused the material to become hairy and locally reducing the thickness of the bundles. Another concern is the dripping that occurred on side when curing.

The sections of the bundles are different for each of the two types. Type A seems to consist of three parallel single roving bundles that interact mainly but not exclusively at the intersections (fig 69). The individual bundles have a circular section with a diameter of around 2 mm and an approximated area of 3 mm. Type B seems to consist of two more flat bundles. At some locations there is air trapped between the bundles and near the intersection points rectangular shaped profiles are formed. The dimensions of the profiles are around 5 mm by 2 mm at each bundle with a section area of around 10 mm. At the location of the removed moulds some residual fibre-less matrix is left in corners (fig 70).

The final concern is caused by the extraction of the mould. Even though treated with a double layer of release agent the removal proved hard. Quite some force had to be applied which might have caused minor cracks in the structure that remained unnoticed.

For the tests additional sheets of plywood are used to ensure that the load is transferred to the wooden ring elements. They create a distance between the fibres around the connection points and the head of the press.



Fig. 67: Some fibres were misplaced during the winding when they got stuck behind one of the connectors. Sometimes this could be solved but in some cases the reinforcements were already placed and the flaw had to be accepted.



Fig. 68: There was an error in the pay-out eye resulting in a knot. This could only be fixed by partially cutting the bundle. Afterwards the winding could proceed with the normal winding bundle.



Fig. 69: The cross section of the bundles of type A did only interact at the intersections.



Fig. 70: The cross section of the bundles of type B interacted better as the intersections were compressed during the process, however, due to the additional layer of reinforcement there was a distance between the first and second polar layer.

8.2.3. Hypothesis

The expected load is calculated using Karamba and basic hand calculations. For more information on the used equations consult chapter 7 'Structural analysis'. The calculations show the maximum performance in perfect conditions for the material, bundle straightness and the intersections. All geometrical input parameters are scaled down to match the physical models and give the maximum load before buckling. The input data is:

E	= 17500 MPa		
σ	= 138 Mpa		
Section	= 3 mm x 3 mm with a surface area of 9 mm		
Lmax	= 80 mm		

The section derives from three circular section bundles with a surface of 3 mm (r=1,9).

The hand calculations provide a critical force of 2783 N at the longest bundle when the effective length factor K = 1,0. If the connections constrain the bending moment K becomes 0,5 allowing for a critical force of 11133 N. The first is assumed for type A, type B might behave more like the latter.

Type A: The maximum load given by Karamba is 30 N per bundle with a total of 2280 N before failure by buckling. The force divided by the surface area should not exceed the yield stress (σ) to prevent fracture. The stress is 6,7 MPa so stays well below the limit for buckling.

Type B: Karamba gives a load of 530 N per bundle and a total of 20140 N before failure by buckling. The stress in the bundles would be 100 MPa so buckling should again be the primary cause of failure.

The output values are assumed too optimistic as the visual inspection showed a high level of voids in the matrix. This will reduce both the elastic modulus and the yield stress. In addition, the bundles might not be perfectly straight due to the effect of stacking the different layers. Finally, the intersections might delaminate when the force causes rotation in the bundles or a shear perpendicular to the fibre direction. In the latter case the yield strength of the matrix will be the weakest aspect of the structure. CES gives this to be 33 to 40 MPa. With the small surface area in the connection of type A this is likely the first part to fail causing the distance between the intersection points to become larger reducing the critical force for buckling.





Fig. 72: The tensile tests are done by clamming the samples and applying a force until it breaks.

tests of the column samples was capable of applying force of 100 kN.

8.2.4. Results

On May 7th the tests are performed on a test bench at the mechanical engineering faculty of the DUT and are done with the aid of experienced engineer P. Eigenraam and associate professor F. Veer.

First the two pillar samples are discussed using the data derived from the tests and the observation during the tests. A load was applied on the top of the columns and the force and deflection were monitored.

The second part is on the tensile tests. The elasticity modulus is calculated using a fraction of the actual stress-strain curve. The difference in stress is 400 N with a starting value of 200 N and an end value of 600 N. The distance between the two pulling heads (L_n) is 220 mm and the samples have a circular profile section with a diameter of 1,9 mm and a surface of 2,84 mm².



Type A samples

_____A1 _____A2 _____A3 _____A4 _____A5

Sample	Force	∆L at break	H model	Deflection ratio
	[N]	[mm]	[mm]	[‰]
A1	3186	1,551	514	3,0
A2	3852	1,811	"	3,5
A3	4291	2,015	"	3,9
A4	3819	1,949	"	3,8
A5	5023	1,839	"	3,6
Mean	4034	1,833	514	3,6



Fig. 73: The results of the type A samples

Type B samples



____B1 ____B2 ____B3 ____B4 ____B5

Sample	Force	∆L at break	H model	Deflection ratio
	[N]	[mm]	[mm]	[‰]
B1	9642	2,455	495	5,0
B2	9312	3,448	"	7,0
B3	10897	2,927	"	5,9
B4	10535	7,011	"	14,2
B5	10207	2,434	"	4,9
Mean	10119	2,816	495	5 ,7



Fig. 74: The results of the type B samples

Observations

At type A the intersection points delaminated after a certain deformation. The bundles forced each other to displace inwards. Typical was the effect of misalignment of the two connection elements which was not noticed until the models were put in the press. It caused two models to deform asymmetrically; one side went inwards the other outwards. Its influence on the capacity was not directly as dramatic as expected since it happened at A1 and A5; respectively the weakest and strongest. Finally the bundles broke instead of bending continuously which shows that the hypothesis of an ever increasing L was incorrect. In that case the bundles should keep on bending, now the intersection points prevented it. The behaviour resembled that of a surface with some exceptions of some loose bundles.

For the type B models buckling of the longest bundles was the primary failure mean. The intersections at the connections were stiff enough to form a bending moment constrained connection, or so it seemed. This behaviour gives the lower bundles a value for K of 0.699 making them assumingly perform better than the one above the first intersection point. The bundles tried to deform as a sinusoid due to the statically indeterminate structure. However, the rotation of the bundle was constrained by the torsional stiffness of the circular reinforcements. Either the bundles fractured next to the intersection or the intersection started to delaminate.

For both model types unexpected behaviour was exhibited when the load was removed. The models formed back to their original shape and regained a part of their stiffness.



Fig. 75: Sample A3 before loaded



Fig. 76: Sample A3 at the maximum deflection of 25 mm still able to resist a 1500 N load



Fig. 77: Detail of sample A5 with the broken bundles. Due to misalignment of te moulds during manufacturing the bundles do not deform symetrically.



Fig. 78: Detail diagram of sample A5 with structural behaviour labels



Fig. 79: Sample 3B before loaded



Fig. 80: Sample 3B at maximum deflection of 22 mm and still able to resist a force of 2000 N



Fig. 81: Detail of sample B3 started deforming right after it had reached the maximum force.



Fig. 82: Detail of sample B1 at maximum deflection



Fig. 83: Diagram of sample B1 with structural behaviour labels



Structural efficiency

Fig. 84: The structural efficiency is a number derived from the maximum force devided by the weight of the composite material. This value makes a comparison of the two types possible.



Fig. 85: The bell's curves show the difference between the specific strenght for the two types and their spread. The standard diviation for A is 1,97 and for B is 1,41. Concluded can be that the addition of the hoop windings makes the structure more efficient.

Scaling

The strength of the models can be scaled towards the proposed 2,8 m pillar. The following two assumptions are therefore made: Buckling is the primary cause of failure and the profile section of the polar bundles are circular. The following equations are thus used:

$$F = \frac{\pi^2 EI}{(KL)^2} \qquad \qquad I = \frac{\pi}{4} \times r^4$$

These equations are then combined and a constant C1 can be retrieved as the material and the connections are assumed the same for the testing models and the full scale product.

$$F = \begin{bmatrix} \frac{1}{4} & \frac{\pi^3 E}{K^2} \\ \frac{\pi^3 E}{4K^2} \\ \frac{\pi^3 E}{K^2} \end{bmatrix} \times \frac{r^4}{L^2}$$

With E = 17500 and K = 1 the value for C1 is 135.652.

$$F = C_1 \times \frac{r^4}{L^2}$$

I (in this case r) is less certain for the tested models then F or L, therefore this taken to be the variable. by reordering the equation the following can be said for the theoretical r:

$$r = \sqrt[4]{\frac{FL^2}{C_1}}$$

F on the pillar is divided by the amount of bundles: 38 and is then 265. L of the longest bundle is 80 mm. This gives a radius of 1,9 mm. This approximates the value as measured at the sample pillars.

The next step is to scale the values, so L is 400 mm and r becomes 9,4 mm.

$$F = C_1 \times \frac{r^4}{L^2}$$

Using the transformed equation for buckling the value for F is 6879 N per bundle or 250 kN for the whole pillar. This is less than the required 292 kN, however, structural capacity seems substantiated.



Tension sample	ΔL_{400}	Elastic modulus	F _{max}	
	[mm]	[MPa]	[N]	
1	1,76	17600	1399	
2	1,60	19388	1517	
3	1,45	21353	1503	
4	1,83	16958	1344	
5	1,58	19594	1489	
Mean		18978	1438	



Fig. 86: The results of the tensile tests. The graph shows one of the tests and the section used for the calculations of the elastic modulus. The values are higher than that those derived from CES but lower than the theoretical elastic modulus.

8.2.5. Discussion

For reliable results the whole process of sample preparation, testing and analysing had to be securely done and structured. To reduce the influence of flaws at least five samples are made. The small scale testing phase lacked proper preparation thus should be regarded as testing the process rather than material or shapes. This is caused by the novel experience of the researcher but was crucial in further process.

The large scale tests are more carefully prepared and done and are therefore more inclusive and useful. The results are promising but not inclusive enough to substantiate the design for the pillar put in practice.

The following can be concluded when comparing the testing results to the calculations of the hypothesis.

Type A: the maximum force was estimated between 2280 N and 2783 N in perfect conditions according to the calculations, the tests show a mean yield force of 4034 N. The elastic modulus and the maximum bundle length of the sample seems close to that of the digital so should not result in such a deviation. The solution is suggested to be found in either the moment of inertia (I) or the effective length factor (K). The influence of I is limited as described in chapter 7.4 'Buckling and its parameters' compared to the influence of K. For the hand calculations the value of K was 1,0, this did not take the following part of the bundle and its stiffness into account. The structure has in this case not been calculated as a statically indeterminate structure.

For the Karamba model the nodes are able to rotate but are bending moment constrained. Therefore the K = 0,5 on bundle part level but 1,0 when looking at the whole structure. No conclusive reason can be given for the behaviour of the digital model and its low output. The software did show similar deflections.

For type B the hand calculations seem to give a relatively accurate result. This shows that the bending moments are constrained at the intersections as seen during the tests. This is promising for the design of the final pillar as it increases the loadbearing capacity.

Karamba shows a result that could be expected as the sample is assumed to perform worse than the ideal situation rendered in the digital model. The sample performed 50% of the calculated strength. This seems reasonable regarding some layers not fully interacting to form a bundle which drastically reduce I. There is, however, one concern that might have influenced the result to an unknown extend. The intersections of the polar and the hoop windings did not always coincide at a single point. In some cases it seems to form a triangular plane which reduces L but created a bending moment transverse to the fibres.

Further research

The following additional research suggested:

- a. The effect of the triangular intersection points instead of coinciding at a single point
- b. Testing new type A samples that have been compacted at the intersections (like type B)

c. Testing with multiple load cycles up to a high percentage of the maximum load. These tests will demonstrate if small cracks appear and what their influence on the structural integrity could be

9. Conclusion

The research started with the question if filament winding could produce a loadbearing pillar whilst achieving aesthetic value by specifically expressing its production technique. Even though the answer is not fully validated in this report the results of the study are promising for both the loadbearing capacity and the aesthetic value.

The structural feasibility is substantiated to be able to carry the load of a pedestrian bridge. Still some research is required on the subjects of weatherability of the material, mould design and structural integrity of the intersection points. This is essential to predict the durability of the product. The current study shows that the required strength can be achieved whilst maintaining acceptable level of openness for aesthetic value. Type B exhibits more structural potential than type A.

The aesthetic value is not quantifiable, however, the open hyperboloid shape is used in architecture, art installations and furniture for more than a century. There can thus be assumed that at least the shape has some. During the study often students and faculty employees came to investigate, comment on and ask about the models. Often these conversations ended in an opinion on the aesthetics, even though probably biased, they were unanimously positive. When asked which type they liked best most preferred type A. A note is added that the type B test sample is not necessarily a perfectly scaled down version of the final design due to the production process.

One of the quantifiable advantages of the pillar is the low weight. For type A this is 95 kg and type B 73 kg for the ideal situation. B could even be reduced to 50 kg. This is, however, for the most ideal situation and the tests show that this is not the case. A material usage increase of 20% as a safety factor has high impact on the bundles moment of inertia and increases the pillars loadbearing capacity. In the case of type A this results in 114 kg and for B this is 89 kg or 60 kg for the optimized design. The weight of the top and bottom connection elements should be added. The low weight has advantages for transportation and assembly on site as now heavy machinery is required. This is particularly useful when constructing on a remote or difficultly accessible location.

CES estimates the material cost for unidirectional glass fibre in a polyester matrix including additives to be 1,50 euro per kg in high volume purchase. The pillar design does not qualify as high volume directly so the price is multiplied by an estimated factor 4. Material cost will thus range from 360 to 648 euro. Finally, material cost is roughly 50% according to Campbell (2010), as the production utilizes conventional filament winding systems this no additional arbitrary factor is applied resulting in an overall cost of 720 to 1296 euro. The cost for the mould should be added. For type A these costs are assumed acceptable when made from steel plating as suggested in chapter 6 'The top and bottom details'. For type B costs will be a multitude due to the moulds complexity.

In a larger context the study fits the growing tendency of applying fibre reinforced polymers in the build environment. The current design is suggested for a pillar of a pedestrian bridge but could in the future also be applied for other columns. The result of the research is not a product which could be produced and used yet; it still requires further investigation and testing. In this process requirements for fire protection or impact resistance might be added.

Future research

The following topics are suggested for further research:

- a. The design of the moulds and the top and bottom elements
- b. The structural effect of the stacked layers
- c. The optimal winding path
- d. Additional functions such as lighting



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Appendix A: Handmade equipment

The flatbed

Build on December 9th the flatbed winding system was made to ease the model manufacturing process. The system consists of a 1 m long M10 steel spindle with nuts between which the mould is compressed. At one side of the spindle a lever was connected to rotate the model. The distance between the supports is 80 cm and they have a height 25 cm.

Moulds

Figure 87 shows The first generation models used acrylic fibres which were elastic and could only be tensioned. The compression went through a PVC tube which remained inside the model. The standard height was 33 cm. The wood used is MDF sheets with a thickness of 12 to15 mm. MDF was the most available material as it was both cheap and shaping was easy in the faculties workshop. The shapes were cut according to a digital drawing to ensure a certain level of precision. The amount of connection points was 60 so an equal division could be made for polygons with different number of sides ranging from three to six. To follow the winding path in the structured models, each of the points is numbered. Before winding this required alignment of the first numbers on the moulds.

For the second generation more precision and a more realistic approach is required (fig 88). Still, MDF was the most available option but for the bigger models cardboard tubes with a diameter of 6 and 8 cm could be used.

For the first composite model was made on a one to six scale with a height of 70 cm. The top and bottom element had the thickness of the designed pillar and consists of three layers of MDF plating. The required angle of 14° and 18° was retrieved from



Fig. 87: MDF moulds with different shapes and a 33 cm long PVC tube held together by the tension of the fibres.



Fig. 88: MDF moulds with the screwed on acrylic tubes for the first GFRP model.

the Grasshopper model. The connection points are made the same way as suggested for the final design; small parts of cut tubes screwed on the two elements the diameter of the tube was five mm which corresponded to the 30 mm for the pillar. The screws for the connection pieces made the MDF delaminate. Additional screws were placed to prevent the cracks to progress. On the top and bottom elements two discs were glued to prevent the hoop reinforcement to slide off. These parts were laser cut in 3 mm MDF sheets.

For the 10 models made for the test the amount of manual labour needed to be reduced. The top and bottom elements did no longer need to represent the actual shape thus could be simplified. In the new design, each element consists of three parts. The connection points and the reinforcements are laser cut, the body element is hand cut and sanded from a single 18 mm thick sheet of MDF. The connection points have a length of 8 mm and a width of 5 mm. The angles of the body are 14° and 16°. The thickness of



Fig. 89: MDF moulds with the screwed on acrylic tubes for the first GFRP model.



Fig. 90: Testing and adjusting the moulds for the type B testing samples.

the wooden ring was around 3 to 4 cm to allow for a strong screwed joint.

The models are named as follows: A letter for the model type, numerical order of winding per type and as a whole. For example A5(8) is the last A type model wound and the eighth of the whole model manufacturing sequence.

For the pillars with the circular reinforcements additional circular mould elements are made. All 11 of these elements had individual diameters and angles (fig 89). The segments were cut in two equal parts to allow extraction after curing, the upper part had to be cut in three due to the limited space. The elements were extracted through the bottom element. The connection of the two mould parts was done by small elastic bands. The force created by these bands caused the friction to hold the elements fixed on the cardboard tube. The tube was cut in two segments at the waist of the column. All parts of the mould were cleaned, sanded and



Fig. 91: Prepairing the type B samples was labour intensive and time consuming. For the final day a fellow student assisted.



Fig. 92: After the curing process the mould had to be extracted manually.

treated with mould release wax twice (fig 91).

Removing the mould took 10 minutes for the type A columns and two hours for the type B column. For the type B extraction some force needed to be applied using a hammer and steel rod. The type B mould was made in twofold and used two and three times.

The fibre disposer

After the first trail with the fibre bobbins the need for a proper disposer was clear. A PVC tube is used to reduce friction and a sponge to keep the fibres together by friction (fig 93). The sponge could be replaced by unscrew the MDF plate. For additional tension the angle to the resin bath could be increased.

The fibres from the second shipment could directly be pulled from the bobbin. The supplier stated that the fibres could be



Fig. 93: The fiber dispencer kept the fibres workable.



Fig. 94: Resin bath 1 had a W shape. All edges inside where sanded to a arc shape to enhance wet-out.

pulled out untwisted, however, this was not the case. This could influence the wet-out in the resin bath.

Resin baths

Multiple resin baths were made during the different stages of the process. The main parameters are the volume, the friction, the nippers and the edge profile for wet-out. A rounded edge was assumed to force the fibres apart. Ideally rollers are used but making them is complex and labour intensive so not fully worth the effort and risk of failure during process.

Bath one: too much friction, poor nipping and low volume (fig 94).

Bath two: used two times, good nipping still to low volume (fig 95).

Bath three: high volume and used 8 times. No glue was used to connect all elements which allowed for easy removal of the leftover set resin (fig 96).



Fig. 95: Resin bath 2



Fig. 96: Resin bath 3 was bigger and could quickly be assambled and disassambled during longer winding processes

Pay-out eye

For the first model in glass fibre no feed eye was used, the fibres are placed by hand with a latex glove. Tension on the fibres was controlled by squeezing the wet fibre bundle by hand. Two major concerns arose; the friction caused nipping the impregnated bundles and glass fibres got stuck in the winders hand. In a normal winding configuration the tension in the fibres is controlled by a tension controller located between the creel and the resin bath. This prevents the nipping effect of the impregnated bundles. This was not possible for the manual winding as it would demand a third person to act as a tension controller or a complex device had to be created.

Primarily the design of the pay-out eye had to incorporate the possibility of being mounted to a robotic arm for process automation. Due to the lack of time and availability of the robot only a first proposal was made. It was, however, never put in to practice (fig 97). The second proposal was a bend steel rod. The diameter of the spiral was equal to the thump of the winder so that it could be used as a braking mechanism (fig 98).



Fig. 97: Pay-out eye 1 was 3d printed. The tensioned piece of plywood acts as a spring.





Fig. 98: The final pay-out eye was a twisted steel rod which could be closed with a thump. the fibres went through the circle.

Drying cabinet

To dry the models and prepare the moulds a special cabinet was made to help handle the different moulds (fig 99). It could hold 4 spindles at a time, which was of great help during the winding process to change the different moulds. During the drying process the most recently made had to be placed at the bottom to prevent dripping on the earlier made.



Fig. 99: The drying cabinet with three models



Appendix B: Images of physical models






































