Delft University of Technology

Literature Study: Fiber-reinforced plastic jetties

By

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Acronyms

CTE	coefficient of thermal expansion.
CUR	Civieltechnisch Centrum Uitvoering, Research en Regelgeving.
DETA	diethylenetriamine.
DGEBA	diglycidyl ether of bisphenol A.
FRP	fiber-reinforced plastic.
HM	high modulus carbon.
HS	high strength carbon.
HT	high tenacity carbon.
ILSS	interlaminar shear strength.
IM	intermediate modulus carbon.
LCA	life cycle assessment.
NEN	Nederlands Normalisatie Instituut.
PAN	polyacrylonitrile.
PEEK	polyetheretherketone.
PP	polypropylene.
PPS	polyphenylene Sulfide.
SLS	serviceability limit state.
SRP	structurally reinforced plastic.
ULS	ultimate limit state.
VARTM	Vacuum assisted resin transfer molding.

Glossary

autoclave	Pressure chamber which regulates both air pressure and temperature.
B-stage	Stage in which the reactiveness of components in a polymer are slowed down significantly by reducing the temperature of the resin. This way, a prepreg can be stored for a certain time span and still be workable after heating up..
curing	The process of hardening thermosets by adding heat,chemical additives or through electron beams. During this process, cross-links are formed..
lamina	One layer of fibers, surrounded by resin.
laminate	A stack of several bonded laminas.
orthotropic material	Material which have different material properties in two or three orthogonal directions.
pot-life	Time needed before a resin is hardened into a solid polymer matrix through cross-linking.
precursor	Raw material of which goods or intermediate goods may be produced from.
prepreg	Pre-impregnated fibers.
spinneret	A device which is used to extrude a molten substance into fibers.
thixotropy	Time-dependent material property that decreases viscosity of a fluid when a shear stress acts upon the fluid.
vibro-pile	In-situ casted concrete pile by utilizing a steel sleeve. In this sleeve, steel reinforcement can be placed..
W-beam	Wide flanged beam.
warpage	Dimensional distortion of a fabricated plastic part after release from the mold.
wettability	The degree to which a fluid is able to maintain contact with a solid.

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1 Introduction

1.1 Research purpose

The literature study is executed with the intent to gain knowledge about fiber-reinforced plastic (FRP) in general, material properties, applications, recent and future developments, durability properties, and sustainability properties. It explores projects and the boundaries of applications of FRP in civil constructions. This literature study is complementary with the master thesis: Feasibility of an FRP Jetty.

1.2 Research questions

More specifically, the literature study aims to answer the following questions: A preliminary lists of research questions is compiled at the start of the literature study. This in order to create a guideline for which topics need to be researched. The following questions have been formulated:

1. What is FRP?
2. What are the advantages and disadvantages of FRP?
3. What are the material properties of FRP?
4. What knowledge regarding mechanics is needed to design FRP composites?
5. How is FRP material produced?
6. In which hydraulic structures is FRP already applied?
7. Are there already FRP jetties and what are their characteristics?
8. What guidelines are available for engineering with FRP in civil engineering?
9. What are the durability properties of FRP? (reparations, life expectancy)
10. What are the sustainability properties of FRP? (C02 emission, recyclability)

1.3 Report structure

The main body of the literature starts with an introduction to composites. Then, Section 4 showcases a few projects where composites are used as a construction material. Section 5 explores the materials of which FRP composites are made and their properties. Then, different manufacturing techniques are presented in Section 6. Section 8 presented information related to the structural design. Several construction units are highlighted. Here, the CUR 96 is elaborated, which is a Dutch design guideline for FRP composites. Also, theory regarding the calculation of laminate properties is presented. In Section 9, joints in FRP construction are explored. Section 10 presents durability related topics for FRP structures. The following section, Section 11, treats the environmental impacts of FRP. Also, this section shortly presents the life cycle assessment, which is used to assess structures and objects regarding its environmental impact. Section 12 gives an overview of costs for FRP composites and structures. Briefly, Section 13 highlights the future of FRP.

Finally, a conclusion is presented in Section 14.

2 Research method

Several students from the Delft University preceded with FRP as a main theme in their master thesis [19][20][21][22].Therefore, general and basic information is already researched in the context of an academic master thesis and readily available. However, still the acquirement of knowledge and the validation of information has to be done, moreover to get myself familiar with the theory and practice of FRP composites and to present a complete thesis. Therefore these sections will be included in detail in the literature study.

Besides the above mentioned MSc theses, important reviewed types of documents are textbooks, like Kolstein's [3] textbook or Nijssen's overal introduction to FRP composites [13]. Mazumdar provides an good book regarding production techniques for FRP composites [2]. Mallick [1] and Nijhof [23] provided excellent books regarding the mechanics of FRP composites. The foremost design guide line in The Netherlands is provided by SBR CUR, the CUR recommendation 96 [5]. Furthermore, articles on bio-composites are used to get an image what will be the development trends for FRP.

Information of the reviewed literature has been put in a structured order of chapters. The information presented builds up on preceding chapters in order to make the document readable and workable.

A draft version of the report was completed in December 2016.

3 Introduction to FRP

As timber, steel and concrete dominated the construction industry for decades, FRP starts to develop itself as a serious competitor due to its, among other, corrosion increased resistance and lightweight properties [3].

In essence, FRP is a composite. In his book, Nijssen [13] uses the following definition:

'A composite is a material structure that consists of at least two macroscopically identifiable materials that work together to achieve a better result'

He further elaborates that the products are not fabricated in one go but separately and that the two components do not dissolve into each other. Also, the favorable properties of both materials are utilized to the maximum. The properties of a particular composite depend largely on their structure, material and manufacturing technique, which Nijssen calls the 'materials triangle' [13].
Also, Nijssen excludes alloys, mixed adhesives and salt solutions in his definition.

In essence, FRP consists of a resin and fibers. There is a wide range of available resins and fibers which each contain different properties. Also, the structure of FRP is highly customizable (e.g. fiber direction, wide variety of resins and fibers). Hence, all properties of a FRP component cannot be formulated. But overall, all FRP's may consist the following advantageous properties related to civil engineering [3, 13]:

– high strength whilst having a low weight;
– highly suitable for customization in form;
– low maintenance costs;
– cost-effective manufacturing processes;
– suitable for customization of specific properties:
  - item strength
  - stiffness
  - thermal resistance
  - electrical resistance
  - abrasion resistance
  - excellent chemical and corrosion resistance

So, these properties make it interesting to look into FRP as a construction material. However, FRP also possesses disadvantageous properties [3, 13]:

– poor ductility;
– stiffness is low compared to traditional and/or competitive materials;
– limited recycling properties for thermosets and even thermoplastics;
– temperature resistance is limited till 150 °C;
– high initial costs due to high material costs;
– long term properties in civil engineering applications are not well-known;

Always when new materials arise, mankind needs to overcome their disadvantageous properties in order to make it lucrative to implement these materials. It is to be expected that these properties will turn up as roadblocks in engineering an FRP jetty. In particular, the poor ductility properties, low stiffness, and the difficulty of constructing joints.

4 Applications of FRP in civil engineering

4.1 FRP civil engineering realizations

Already construction consists made of FRP [10]. This section will explore a few of them.

Figure 1: Ehpemeral Cathedral of Créteil, France. This build is a first one of its kind, a grid shell structures made of composite materials [9]. It encompasses a surface area of 350 m^2.

Figure 2: Friedberg Bridge, Germany. This bridge has a width of 5 m and a span of 27 m. A multi-cell platform deck made of FRP profiles rests on two steel beams. The deck and the beams were glued in-sito to each other [10].

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Figure 3: Floriade bridge, The Netherlands. This pedestrian and bicycle bridge can support vehicles up to 12 tonnes. It has a width of 6 m and spans 127.5 m. The GFRP deck rests on steel beams [10]

Figure 4: Spieringsluis, The Netherlands. This is the first FRP lock gate constructed and installed in The Netherlands. Two panels with a width of 3.5 m each compose the gate. The panels have a height of 6.5 m

Regarding the application of FRP to jetties, several examples have been found. However, no jetties made fully out of FRP were found during the desktop research (besides small floating jetties). Structural components such as bolts and piles were frequently made of steel and wood. Also, FiberCore Europe, a leading FRP company in civil engineering applications, has been contacted which stated that they (yet) have no experience designing and constructing FRP jetties. They were not familiar with companies in their network which has experience with FRP jetties [24]. In literature studies of students whose thesis topics were related to FRP, in general bridges, sluices and lock gates are mentioned but no jetties [19].

In the harbor of Warmond, The Netherlands, van der Poel BV has constructed an plastic jetty. The plastic is not reinforced with fibers. This is because if the jetty is hit by impact, FRP tends to shred resulting in a lot of splinters. Therefore, the slabs are reinforced with 4 steel rods to make it ductile resistant. The fibers were to cause of the splinters, not the resin [11]. Also, beams reinforced with steel had a larger span (4 m) compared to the FRP beams.
The wooden piles are guarded by a plastic pile head. This pile head covered the area of the pile which was prone to rot: this is the area above the level which if always submerged.

(a) View of fingerpiers

(b) View of a joint

Figure 5: Partial FRP jetty constructed by van der Poel BV [11]

5 Material properties

In this section, the materials and their properties used in FRP will be explored.

FRP exists of fibers and a polymer matrix, which is made from a resin. Also, coupling agents, coatings and fillings may be used in the production of FRP [1]. A composite is manufactured by stacking thin lamina, or plies, to form a laminate. A lamina is a thin layer of the matrix mainly formed by fibers and resin (besides optional coupling agents, coatings and fillings). These lamina are then consolidated into a single matrix which forms the laminate. Material properties of the composite depend greatly on the fiber direction. In Figure 6 different fiber patterns are illustrated.

Depending on the different material combinations, different names are used to refer to the different composites. Polymer Matrix Composites or Fiber Reinforced Polymers (PMC's and FRP, respectively) refer to reinforcing fibres in a matrix based on a polymer resin. Metal Matrix Composites (MMC's) relates to a composite with at least one metal material and Cermaic Matrix Composites (CMC's) relate to a composite containing at least one ceramic material. If a composite constitutes more than two different materials they are also called hybrid matrices [25].

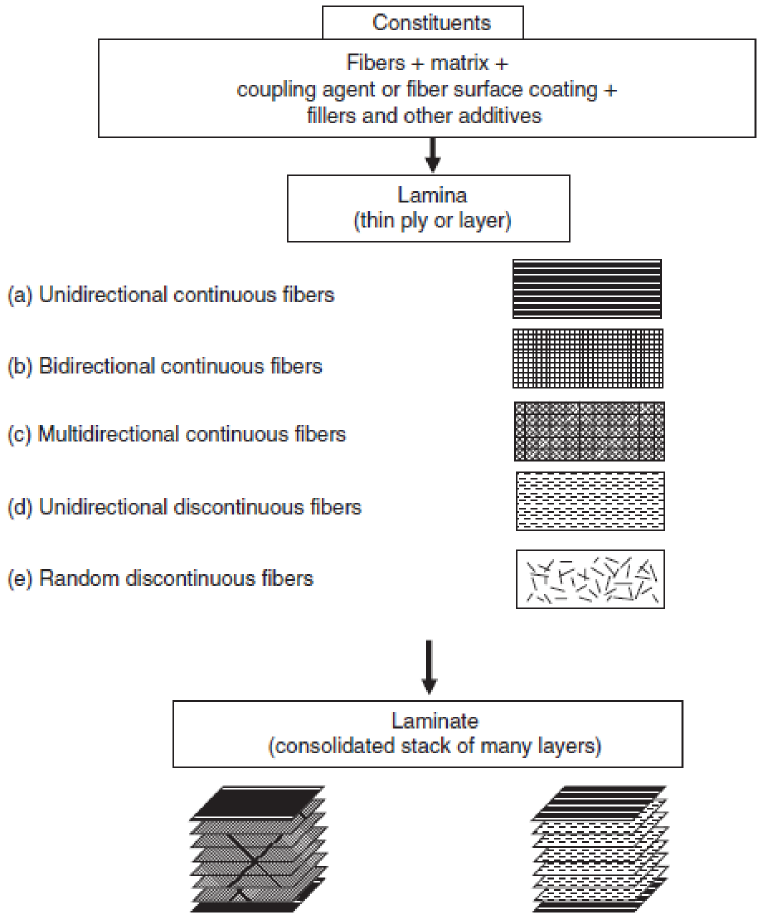


Figure 6: Fiber directions illustrated by Mallick [1]

5.1 Fibers

The fibers in a composite occupy the largest volume in a composite and their main function is to bear the load on the composite. The strength and stiffness of the composite is mainly determined by the material properties of the fibers [13].
Therefore, knowledge regarding fibers is important if a composite is composed. The following properties depend largely on the fiber material, volume fraction, length and orientation:

– Density composite
– Tensile strength and modulus
– Compressive strength and modulus
– Fatigue strength as well as fatigue failure mechanisms
– Electrical and thermal conductivity
– Costs [1]

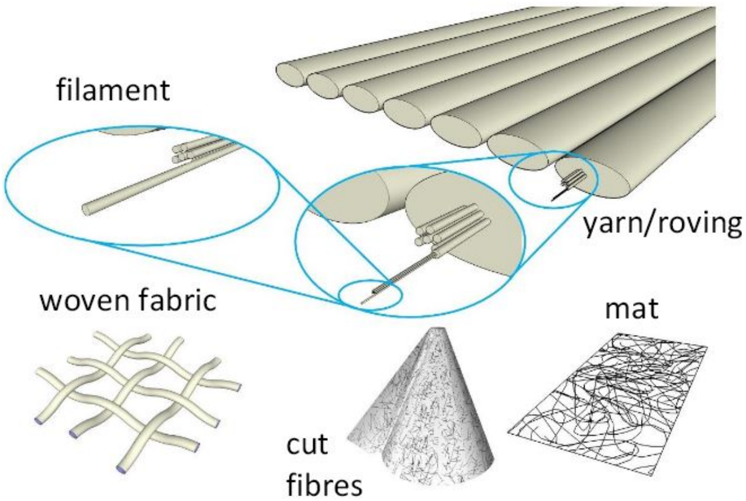
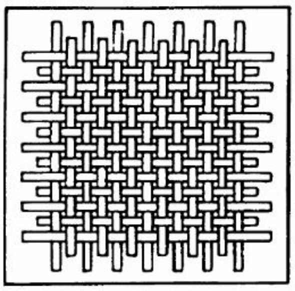


Figure 7: Different elements and compositions of fibers

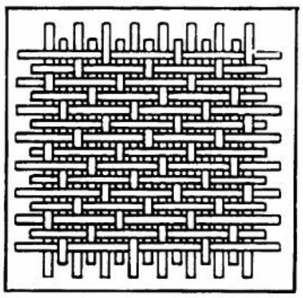
Figure 7 illustrates different elements and compositions of fibers. Wires are typically very small (in the order of 10 µm). The wires, also called filaments, can be made more workable binding them in bundles, also called roving. These bundles can be twisted or untwisted. For glass, an untwisted bundle is called a strand or end. For carbon a bundle is called a tow. If the bundle is twisted it is called yarn [1]. These bundles can be used separately for production techniques like filament winding and protrusion. Also they can be woven into fabrics with a variety of patterns. Kolstein lists several of these fabrics [3].

Chopped strand mat (CSM)	Chopped strands are small lengths of fibers which are laid down in a random pattern and they have therefore a unidirectional orientation. The strands are hold together with a thermoplastic binder.
Continuous filament mat (CFM)	Fibers are random laid down in a straight or swirl pattern in all directions. The fibers are hold together with a thermoplastic binder.
Woven fabric	In a woven glass fabric, bundles of fibers are woven into a mat. Different weaving patterns are used to produce a mat.

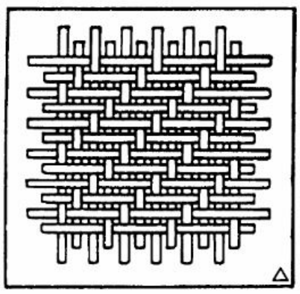
They way bundles of fibers are woven into a pattern dictates certain properties for the resulting mat. Some weaves are more flexible in imposing forms than other weaves. This property is called drapeability [13]. However, fiber direction in weaves with better drapeabilities have less directional freedom. Weaves such as twill and stain, which are looser weaves, show better drapeablility and permeability. Smooth weaves on the other hand, provides more stability. Several weave patterns and their properties are described by Kolstein [3]:



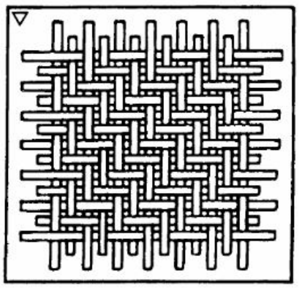
Plain weave. Good distortion resistance and reproducible laminate thickness.



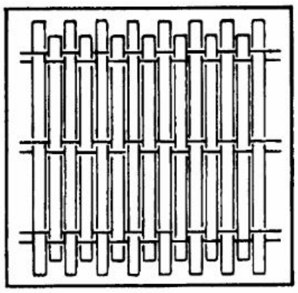
Twill weave, 2 on 2. This weave pattern has good drapability.



Twill weave, 3 on 1.



Satin weave. This weave has excellent drapability and imparts high properties to laminates.



Unidirectional weave. Maximum tensile properties are obtained in the warp direction with these fabrics [3].

Fibers come in a big variety of materials like glass, carbon, basalt, and aramid. For the application of FRP, especially in civil engineering, glass fibers are most used because of their relative low costs and excellent strength properties [3].The next section describes a selection of several fibers which might be relevant to the purpose of this study. An overview of material properties of different fibers is presented in Table 1.

Different sources provide different values for the material properties of wires. In Table 1, conservative values are presented based on different literature [2, 1, 3]. In general, the E-moduli presented by different sources were alike, whilst tensile strength properties presented by Kolstein varied greatly. Table 1 embeds the tensile strength given by Mallick and Mazumdar [2, 1].

Material	E-Modulus [GPa]	Tensile strength [MPa]	Elongation [%]	Density [kg/m^3]	Poisson's Ratio [$-$]
Glass					
E-glass	70	3450	4.8	2450	0.2
S-glass	70	4300	5	2490	0.22
Carbon					
High strength carbon	240	2600	0.8	1860	-
High modulus carbon	345	1800	1.5	1700	-
Polyaramid					
Kevlar 49	131	3620	2.8	1450	0.35
Natural fibers					
Hemp	70	550-900	1.6	1480	-
Flax	60-80	800-1500	1.2-1.6	1400	-
Sisal	38	600-700	2-3	1330	-
Jute	10-30	400-800	1.8	1460	-

Table 1: Material properties of a selection of fibers [1][2][3]

5.1.1 Glass fibers

Glass fibers are used because they have a high tensile strength, chemical resistance and insulating properties for low costs [1]. Commercial glass fibers are supplied in different classes are described by Gómez:

A-glass	Alkali glass, once widely used but now is replaced by E-glass in many applications
C-glass	Chemical resistant glass used mostly as surface tissue because of its superior resistance to environmental conditions, impact, and abrasion
D-glass	Mainly used in electronics industry due to its good electric properties
E-glass	Electrical grade glass (low alkali content borosilicate glass, good electrical, mechanical and chemical properties)
R- and S-glass	High strength glasses used mostly for aerospace applications [25]

Glass fibers are made out of silica sand, limestone, fluerspar, boric acid, and clay, with silica being the mayor component among the ingredients [2]. In Figure 8 an overview of the glass fiber production is illustrated.

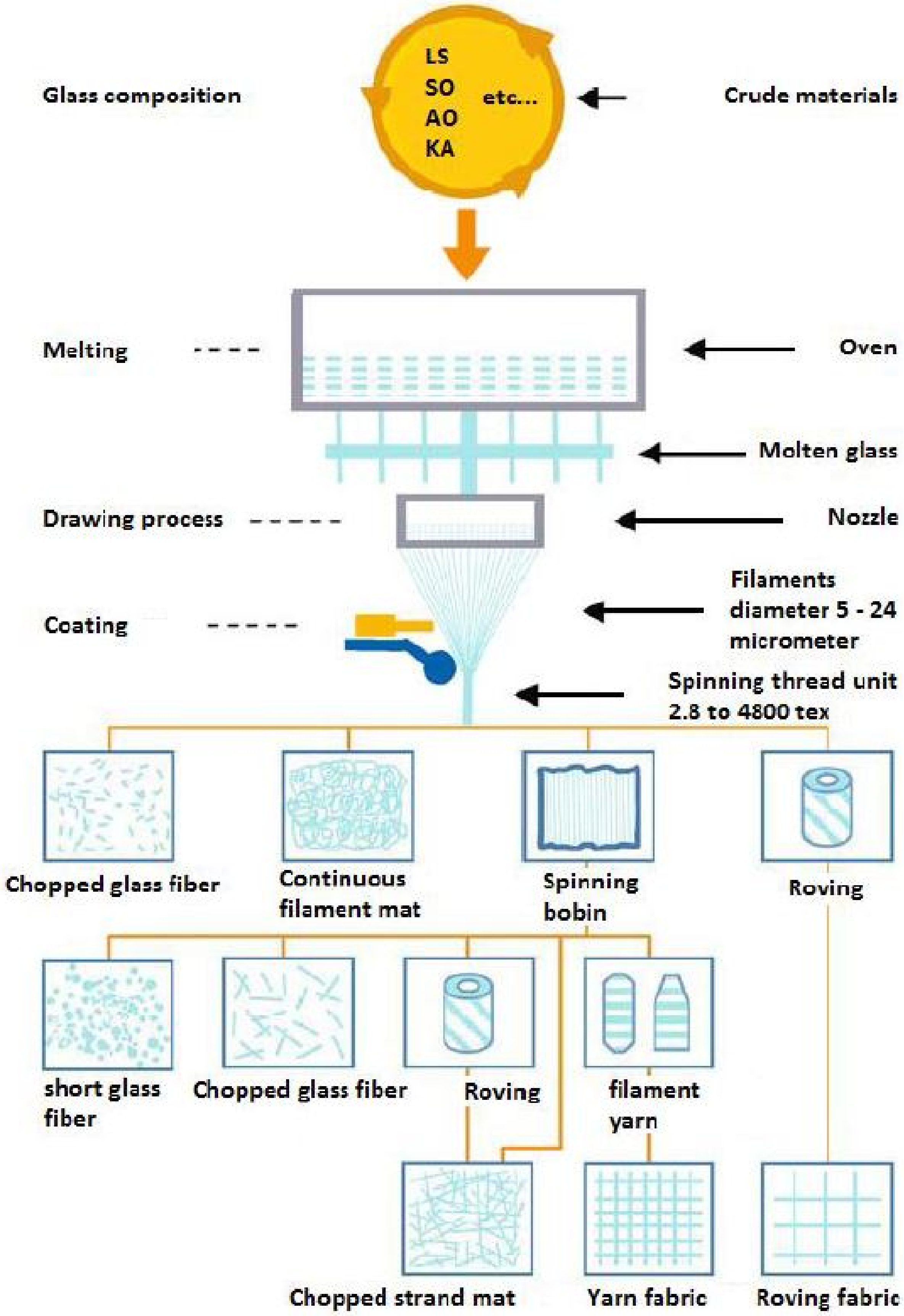


Figure 8: Overview of glass fiber production [12, p27]

5.1.2 Carbon fibers

Carbon fibers are often used in applications were big forces are impound on a structure and costs are not a primary concern. Typical field are the aerospace and high end automotive industry. The higher tensile strength properties of carbon fibers come at a price: they are significantly more expensive than their glass counterparts [3]. Carbon fibers are very light: this gives them very high tensile-strength to weight and high module to weight ratios [1]. Other advantageous properties are their high fatigue strengths, high thermal conductivity and, a low coefficient of thermal expansion. However, their strain is low when they fail, making them non-ductile. Also, their impact resistance is low due to this low ductility.

In the carbon fibers, both amorphous (non-crystalline) and graphite carbon is present (see Section 5.3 for an explanation of amorphous and crystalline materials). The latter is responsible for the high strength properties of carbon fibers. The carbon molecules form regular hexagons, which are linked to form long crystalline graphite chains. These chains are orientated in the fiber direction. Because of this the properties of the fibers are different in the direction of the fiber axis than in the transverse direction. The arrangement of the crystalline chains in the fiber influences the properties of the fiber, see Figure 9 by Mallick [1].

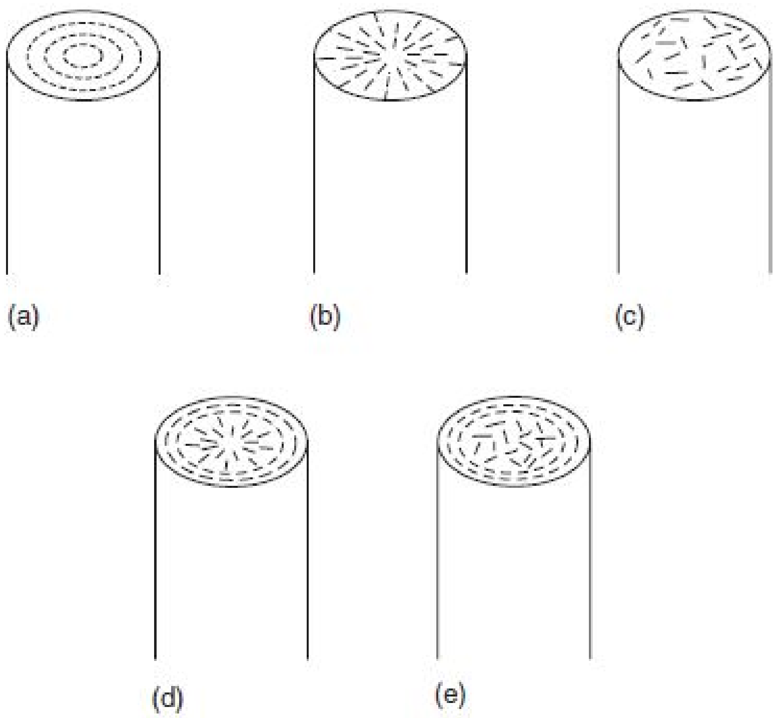


Figure 9: Arrangement of chains in carbon fibers relative to the axis fiber: (a) circumferential, (b) radial, (c) random, (d) radial-circumferential, and (e) random-circumferential. Image and text from Mallick [1].

There are two main precursors for carbon fibers which are polyacrylonitrile (PAN) and pitch precursors [2]. PAN is a textile based precursor. The fibers are formed by wet spinning and stretching them. Then, the fibers are heated at 1000 °C to 2000 °C whilst under tension. This rearranges the chains and purifies the fibers, getting rid of excess oxygen and nitrogen atoms. This process is called carbonization [1]. The results is a

filament with a relatively low E-modulus with high strength. Then, relatively high E-modulus fibers can be obtained by graphitization. Graphitization takes place during heating of the filaments, only now temperatures reach above 2000 °C [1]. In this process, the structure of the filaments becomes more ordered and reaches a graphitic form. Whilst the modulus of the carbon fibers increase due to graphitization, their tensile strength tends to decline and become relatively low.
For pitch carbon fibers, the process of carbonization and graphitization is the same. Only the way the filaments are manufactured from the precursor is different. Now, pitch filaments are formed by extruding a highly viscous state of pitch, called a mesophase, through a spinneret. For the pitch to be in a mesophase its temperature needs to be in a range of 300 °C to 500 °C [1].

5.1.3 Aramid fibers

Polyaramid fibers are used in a wide range if lightweight applications where high tensile strength is required. These fibers have the highest tensile-strength to weight ratio [1]. These fibers find not a lot of applications in structural elements due to their high costs. Therefore, this section will be limited.

An example of a polyaramid fiber is Kevlar 49. Kevlar 49 is manufactured by an extrusion and spinning processes [3]. The molecules tend to orientate themselves in the direction of the fiber and are bonded among each other by weak hydrogen connections. This may explain their weak resistance to compressive forces. However, in bending, the compression side shows a high degree of yielding. This gives Kevlar a better impact and dynamic load resistance than glass and carbon fibers, which do not posses such high degree of yielding [1]. Furthermore, polyaramid fibers have a good resistance to heat and wearing.

5.1.4 Natural fibers

A lot of plant-based resources in the natural world are suitable as a raw material for fiber production. Some of these are flax, jute and soy. Recently they have come under the attention because of the following reasons.

Unlike carbon fibers and glass fibers, natural based fibers are bio-degradable. This means that natural processes can decompose the fibers. So instead of burning or recycling, it can be decomposed. This is a huge advantage regarding the environment. Also, manufacturing of natural fibers costs less energy than the manufacturing of glass and carbon fibers.
Another advantage is the low weight of natural fibers. The density of natural fibers range from $1.25\,g/cm^3$ to $1.5\,g/cm^3$. This is low compared to the density for E-glass fibers $\left(2.54\,g/cm^3\right)$ and for carbon fibers $1.8\,g/cm^3$ to $2.1\,g/cm^3$ [1].
Because of the low density of natural fibers, their modulus-to-weight ratio can still be high. In some instances, the modulus-to-weight ratio even surpasses that of E-glass.
Besides the above mentioned, natural fibers are readily available and cheap compared to glass fibers and carbon fibers.

Apart from the advantages, natural fibers also have disadvantageous properties. Table 1 illustrates the E-moduli of different fibers and here can be seen that the tensile strength properties of natural fibers are significantly lower than those of glass fibers and carbon fibers.

5.2 Matrix

The polymer matrix has four different functions:

– Fixing the fibers in the desired geometrical arrangement
– Transferring the forces to the fibers
– Preventing buckling of the fibers under compression actions by giving sideways support
– Protecting the fibers from external forces such as humidity etc. [3]

In contrast to fibers, the matrix does not carry big tensile capacities. But, the matrix influences the compressive, interlaminar shear and the in-place shear properties of the composite greatly [1]. Also, the interaction between the fibers and the matrix dictates the damage tolerance. Therefore the matrix material should be chosen carefully.

Matrices come in a variety of materials. Examples of these materials can be polymers, metals or ceramics. In the construction industry the main focus lies on polymer matrices [3]. Metal, ceramic, and basaltic matrices will not be treated because they lie beyond the scope of this thesis.

5.3 Polymer matrix

Polymer, or plastic, matrices have two unique characteristics in a solid state. First, the mechanical properties depend on the temperature. Secondly, the mechanical properties depend on the loading state [1].

Several states of polymers occur at different temperatures. The melting temperature is denoted by T_m. At the (crystalline)melting temperature, the polymer structure is transiting from a semi-crystalline structure to an amorphous structure. In a crystalline structure, molecules are arranged in an orderly fashion. In an amorphous structure, molecules are arranged at random. Semi-crystalline refers to a structure where areas of the material are in a crystalline structure and the rest of the material is in an amorphous structure [2]. At the glass transition temperature, denoted by T_g, the polymer changes from a hard, solid state to a soft, thought material. The polymer is highly viscoelastic around the glass transition temperature [1].

Plastic can be divided in two general categories: thermoplastics and thermosets. The main difference is that thermoplastics melt and can be remolded above their melting temperature, whilst thermosets cannot be remolded and will decompose at a certain temperature. This occurs due to the structure at molecule level. Essentially, plastics are polymers. Polymers are long organic chains, bonded by strong covalent connections [3].
Thermosets are hardened during curing. Curing is the process of hardening of a polymer material by adding heat, chemical additives or electron beams. During this process, irreversible connections are formed, called cross-links. These cross-links connect the long polymer chains to form a solid matrix. Thermoplastics don't have cross-links. The polymer chains in thermoplastics are not interlinked. The chains stick together due to Van der Waal forces or hydrogen bonds [1]. This is also the reason why they melt and can be remolded when reaching their melting point. In Figure 10 an image of polyester chains and cross-links is presented.

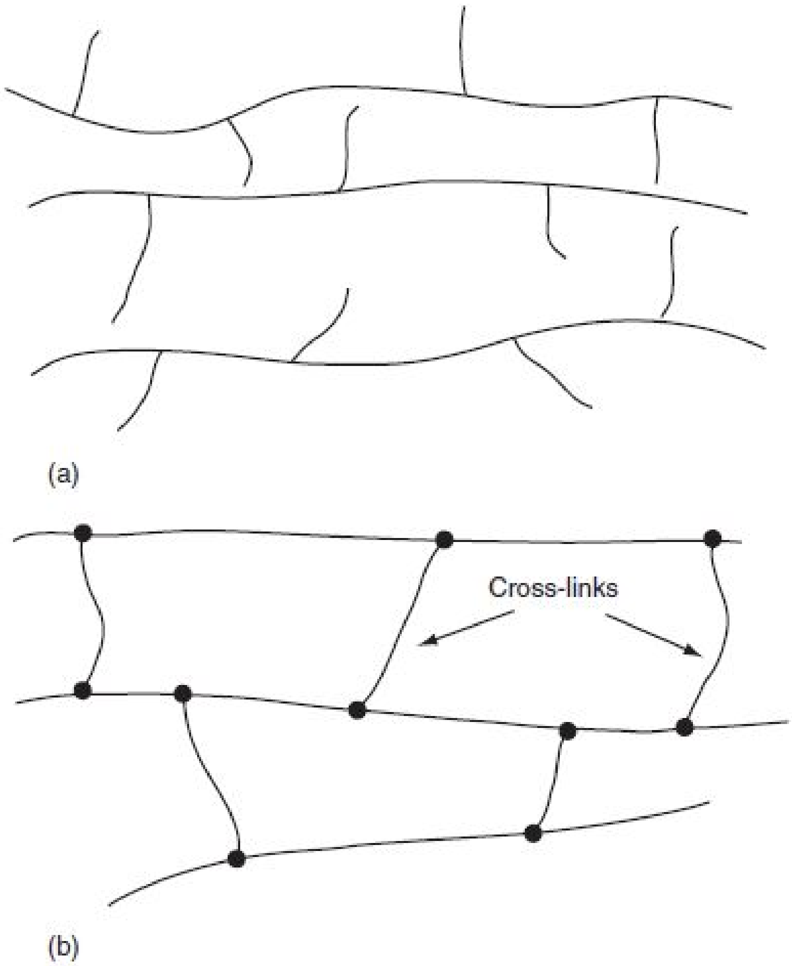


Figure 10: Schematic representation of (*a*) a thermoplastic polymer and (*b*) thermoset polymer. Image and text from Mallick [1]

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The cross-link density in a polymer matrix influences several material properties of the matrix. In general, the following advantageous properties increase with increasing cross-link density: tensile modulus, glass transition temperature, thermal stability, and chemical stability increase. Disadvantageous properties with increasing cross-link density are reduced strain-to-failure and fracture toughness [1].

The volume shrinking has to be considered as well. Polymers which shrink a lot during curing are easier to remove from a female mold in an open mold process (see Section 6). However, with a high shrinking volume, sink marks on the molded surface may form. Sink marks are depressions as a result of the different in shrinkage between the polymer and the reinforcement fibers. This is undesirable if aesthetics is a desired property [1].
Thermosets and thermoplastics both have their advantages and disadvantages regarding their applicability as a matrix in a composite.
Thermosets often have a low viscosity when they are applied to fibers, hence no high temperatures or pressures are need to assure adhesion. This adhesion, also called fiber surface wetting, is very important because it heavily influences the fiber-matrix interaction. This is important in order to achieve a good mechanical performance. Compared to thermoplastics, they have a good thermal stability, chemical resistances and show less

creep and stress relaxation.
Thermoplastics show high impact strength and have a good fracture resistance compared to thermosets. This is due to their high strain-to-failure characteristics. They posses good damage tolerance characteristics compared to thermosets because of this characteristic.
The fabrication time of thermoplastics is shorter than that of thermosets. Also, thermoplastics have an unlimited shelf life in contrary to the shelf life of thermosets, which is limited.
Regarding the reprocessing and recycling capabilities, thermoplastic have a far bigger advantage compared to thermosets. Thermoplastics posses this capability because they can be remolded above their melting temperature. Thermosets will fracture down above their melting temperature. Therefore they are not suitable for reprocessing.

Concluding the above, both thermoplastics and thermosets have distinctive and desirable properties. However, thermosets are far more used in the fabrication of composites. This is because it is easier to incorporate continuous fibers into matrices of thermosets than of thermoplastics. This greatly influences the adhesion between fibers and the matrix and determines their mechanical performance to a great extend [1].

Material property	Thermosets	Thermoplastic
Ease of incorporating continuous fibers into the matrix	Relatively easy	Very difficult
Strain-to-failure	Low	High
Creep	Low	High
Stress relaxation	Low	High
Chemical resistance	Excellent	Moderate
Thermal stability	Excellent	Low
Fabrication time	Long	Short
Storage life at room temperature	Limited	Unlimited
Tackiness	High	Very low
Presence of volatile matters during curing	Yes	No
Postformability capabilities	None	Possible
Reprocessing and recycling capabilities	Bad	Good

Table 2 presents an overview of different thermoplastics and thermosets and important mechanical properties.

Material	Density $[kg/m^3]$	Tensile Modulus [GPa]	Tensile Strength [MPa]
Thermosets			
Polyester	1100–1400	1.6–4.1	35–95
Phenolic	1200–1400	2.7–4.1	35–60
Epoxy	1200–1400	2.5–5	35–95
Thermoplastics			
Nylon	1100	1.3–3.5	55–90
PEEK	1300–1350	3.5–4.4	100
PPS	1300–1400	3.4	80

Table 2: Different polymer resin materials and their properties by Mazumdar [2]

5.3.1 Thermosets

Thermosets come in a variety of polymers. The most applied with respect to FRP are listed here [2, 13, 1]. Mentioned manufacturing processes can be found in Section 6.

Polyesters are long unsaturated chains which are mixed with a reactive monomer, such as styrene, in order to form a matrix. The styrene molecules bind themselves to the polyester chains by carbon-carbon double bonds and these make up the cross-links. A catalyst is added to speed up the curing time. During curing, no pressure is needed to form a solid. The curing happens in four stages: the induction period, gelation, exotherm build up and the final hardening stage [3]. In the induction period, free radicals are being formed which react with the inhibitor. In the gelation stage, the solid network forms due to the cross-links. At last, final hardening will take place, which can take days or weeks.
Polyesters are used a lot due to their low price [13]. Furthermore, they posses an excellent corrosion resistance. In manufacturing processes, polyesters are used for pultrusion, filament winding, (SMC, and RTM operations) [2].

Vinylesters are produced by mixing an unsaturated vinyl ester with a styrene monomer. The main difference between an unsaturated polyester and an unsaturated vinyl ester is that vinyl esters only have double carbon bonds at the end of the molecule. Therefore, the amount off cross-links is not as big as with polyester monomers [1]
In manufacturing processes, vinyl esters are used for pultrusion, filament winding, (SMC, and RTM operations) [2].

Epoxy resins are formed differently than thermoset polyesters and vinyl esters. The polymer matrix is formed by mixing two components: an epoxy group and a hardener (also called a curing agent). A commonly used epoxy group is diglycidyl ether of bisphenol A (DGEBA). DGEBA has two epoxide groups which can be linked trough a hardener. Diethylenetriamine (DETA) is a widely used hardener. Once the two materials are mixed, the mixture starts curing and the epoxy matrix is formed.

Epoxies have good adhesive properties. Therefore, they add well to a lot of materials, fillers, and fibers. That is why epoxy matrices can be very versatile: material properties can be influenced by adding chemical compounds. At room temperature they function well, but for higher levels of heat resistance capacity costs will increase. Also, epoxies matrices have good corrosion resistance and chemical resistance.
Epoxies shrink less compared to other polymers, hence they are better workable during the manufacturing process. Manufacturing processes used to produce composites with epoxies are filament winding, hand lay-up, pultrusion, RTM in their liquid form. In a semi-solid form they are used in autoclave processes and vacuum bagging (Section 6).

5.3.2 Thermoplastics

Thermoplastics are less used in composites. Because of their high viscosity in their liquid state they are in general not suitable for impregnation of a fiber reinforcement. Impregnation is the wetting of the fibers. Because of this, the composites cannot be formed in a stable way. Therefore, for the usage of a thermoplastic matrix, high pressure and temperatures are needed during the production process [13].

Compared to thermosets, thermoplastics have good toughness, resilience and corrosion resistance [3]. Therefore, more research involving the usage of thermoplastic matrices is taking place lately. Next to the above mentioned disadvantages of thermoplastics during molding, when finished, they have lower levels of heat and solvent resistance. Also, their creep resistance is bad [2].

Thermoplastics come in a variety of polymers. Figure 11 illustrates different thermoplastics, divided by their amorphous or semi-crystalline material type [26]. Also, performance categories are presented.

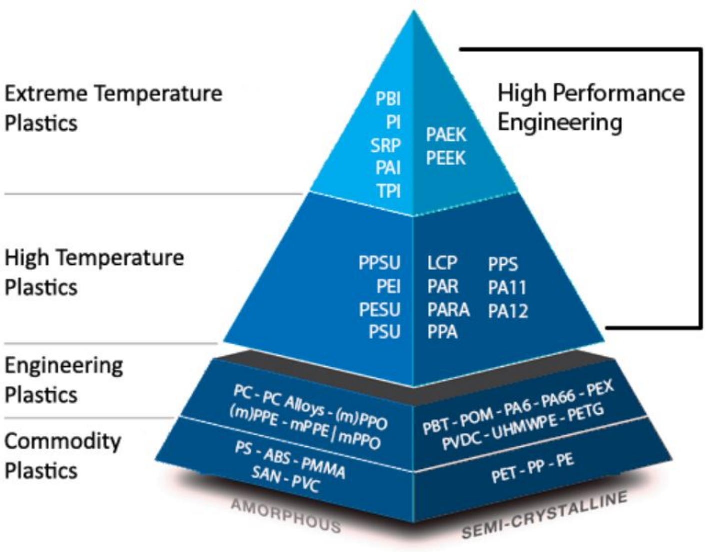

Figure 11: An overview of thermoplastics, dived by amorphous or semi-crystalline material type and performance catagory

The most used thermoplastics are described by Mazumdar [2](mentioned manufacturing processes can be found in Section 6):

Nylons come in several types like nylon 6, nylon 66 and nylon 11. Each of these types offers different material properties. In general, they are considered engineering plastics. A material property of nylons which needs to be taken into account during the design process, is that they absorb moisture. This is influences the properties and the dimensional properties of the composite. In combination with glass fiber reinforcement, this problem is minimized. In the production process, nylons are available for injection molding purposes and as prepregs (see Section 6.3.2).

Polypropylene (PP) is available in many grades. PP is inexpensive, light weight and versatile. It offers good strength, stiffness, chemical resistance, and fatigue resistance [2].

Polyetheretherketone (PEEK) is a next-generation thermoplastic which has a high heat resisting capacity. Therefore, it is used a lot in the aerospace industry. Another advantage of PEEK is its low water absorption, which is approximately 10 times lower than other aerospace-grade epoxies. Also, the toughness of PEEK is 50 to 100 times higher than other epoxies. These advantages come at a high cost: PEEK is a very expensive polymer.

Polyphenylene Sulfide (PPS) has very good heat resistance capacities. Also, it has a good dimensional stability, chemical resistance, and flame resistance. PPS has very good mechanical properties [26].

5.3.3 Overview polymer matrices

Table 3 presents and overview of the advantageous and disadvantageous material properties of the most common polymer matrices used in the FRP industry.

Material	Advantages	Disadvantages
Thermosets		
Polyester	Relatively low costs	high curing shrinkage
	low viscocity	presence of volatile matters during curing
	fast curing time	low heat resistance
	good chemical properties	
	good electrical properties	
Vinyl ester	excellent tensile strength	high curing shrinkage
	excellent chemical resistance	presence of volatile matters during curing
	good fatigue resistance	moderate adhesive strengths
	low viscosity	low heat resistance
	fast curing	
Epoxy	wide range of customizable properties	relatively high costs
	excellent adhesion	brittle in general
	excellent chemical resistance	long cure time
	low shrinkage during curing	
	absence of volatile matters during curing	
	good thermal properties	
	very good electrical properties	
Thermoplastics		
Nylons	toughest thermoplastic	
	high melting point	
	high elongation	
	absorbs moisture	
	good surface appearance	
	good lubricity	
PP	low cost	
	low density	
	good strength	
	good stiffness	
	good chemical resistance	
	good fatigue resistance	
PEEK	high glass transition temperature	very high cost
	excellent heat resistance capacity	
	very good damage tolerance	
	good solvent resistance	
PPS	high operating temperatures	

Table 3: Overview of advantages and disadvantages of polymer matrices [2, 1, 3]

5.4 Prepregs

A prepreg is a pre-impregnated fiber, fabric or mat. These intermediate products are used in the hand lay-up or molding operations [2] (See Section 6.3.2). Once the resin is applied, this will start to cure, forming cross-links between the molecules. The time which is needed to saturate the polymer with cross-links, so it becomes a solid matrix, is called the pot-life [1]. Once the pot-life has passed, the polymer matrix is solid and the prepreg will be unable to be processes in molds because it has lost its flexibility. That is why, in general, after impregnation, the prepreg is stored at a cold temperature. This slows down the curing speed and significantly increases pot life. So, the prepreg is semi-cured at this stage, which is also called the B-stage [1]. In this stage the prepreg is tack-free, making it very workable. When the prepreg is needed for production, it can be taken back to room temperature in order to make it more workable. There are also prepregs available which have long pot life at room temperature. For instance, Fiber Glast Development Corporation provides carbon prepregs which can be stored for a year at room temperature[14]. The curing process is initiated by applying both heat and pressure. This pressure can be readily supplied by a vacuum.

Prepregs can be coated with thermoset and thermoplastic resins and the usage of prepregs has several advantages and disadvantages [14]. For thermoset prepregs, an advantage is that they can contain a low resin content up to 35 %. With traditional hand lamination, where fabric fiber sheets are alternated with layers of resin, this lies around 50 % because it is difficult to obtain lower resin volumes. Hence, the composite has an excess of polymer material. This reduces the overall mechanical properties of the composites. Another advantage is that the application of prepregs is its uniformity and repeatability. No additional resin is applied since this is already processed into the prepreg. Therefore, and uneven distribution of resin is prevented. This increases that parts will be similar when produced with the same mold. Also, less waste and mess is generated because of this.
The main disadvantage of prepregs are its high costs [14]. Even the combined costs of the resin, fabrics and curing, prepregs are still more expensive. Another disadvantage is that a prepreg has a shelf life, or pot-life, in contrast to stocked resins and fiber mats. However, as noted before, there are prepregs with substantial shelf life which can span up to one year. A last disadvantage is that a heat cure is necessary in combination with pressure. Other resins may cure at room temperature.

Thermoplastic prepregs have several advantages over thermoset prepregs. Mazumdar lists some of these advantages:

- Recyclability
- Good solvent and chemical resistance
- Higher toughens and impact resistance
- Indefinite shelf life with no refrigeration
- Reshaping and reforming flexibility
- Greater flexibility for joining and assembly by fusion bonding and *in situ* consolidation
- Better repairability potential [2]

Mazumdar states that the disadvantages of thermoplastic prepregs are they require higher processing temperatures and pressure [2]. Also, their adhesion capabilities to fibers proves difficulties during the production process.

5.5 Core material

Core materials are used to construct sandwich panels. Sandwich panels provides the highest stiffness-to-weight ratio and strength-to-weight ratio [2]. A sandwich panel consist of two laminates separated by a core. These laminates are called the skin of the sandwich panel. Now, with the same amount of material used for the laminates, with the aid of cores better cross-sectional properties can be acquired. Often, the cores will function as distance holders to increase the second moment of area with respect to the central bending axis generated by the laminates. Other functions of foam are to increase sound and fire insulation, and creating a larger volume without much additional weight. Figure 12 illustrates a sandwich panel with a honeycomb core.

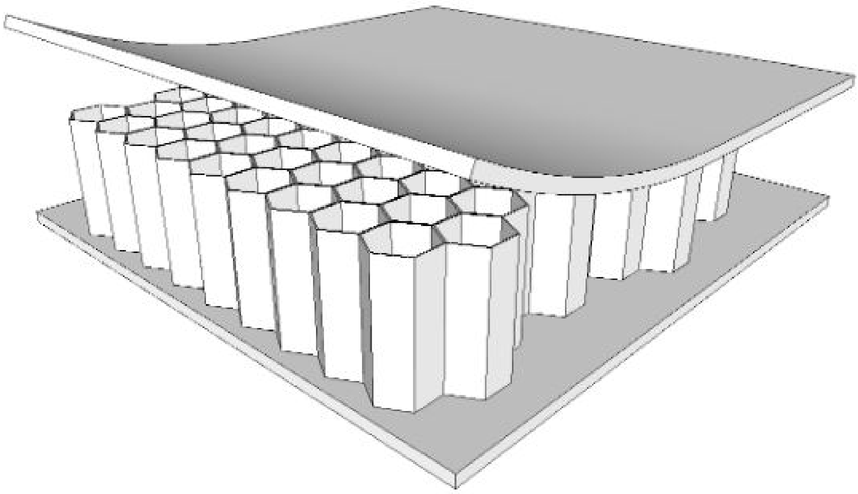

Figure 12: Sandwich material using a honeycomb core [13]

Examples of core materials are foams, honeycomb structures, plastics, wood, aluminum and pyramids. Figure 13 presents three commercially available cores from Fibre Glast Developments Corporation. The honeycomb structures they sell are the most expensive, followed by foams, and lastly the balsa wood.

(a) Honeycomb (b) Foam (c) Balsa

Figure 13: Common core materials [14]

Honeycombs are core materials which are structured like honeycombs. Figure 13a shows a honey comb with a hexagon structure. The honeycomb is frequently made from aluminum, Nomex (flame resistant meta-aramid), polycarbonate, and polypropylene [2]. Thermoplastic honeycombs are flexible and can be used in curved sandwich panels. More often, honeycombs are applied in in flat sheets. The two main ways to produce honeycomb cores are expansion and corrugation [1].

5.6 Fiber surface treatments

In order to reassure a good connection between the fibers and the matrix, fiber surface treatments are used. This will increase the wettability of a fluid. The wettability of a fluid is the degree to which it is able to maintain contact with a solid. Also, a strong bond at fiber-matrix interface will be created. For an effective stress transfer between fibers and the matrix, both the wettability and the bond at fiber-matrix interface are important [1].

5.6.1 Glass fibers

Chemical compounds can be used to improve the strength in the fiber-matrix interface. Also, the fiber surface can be protected from moisture and reactive fluids.

In order to treating glass fibers they first have to be cleaned. This is done by heat-cleaning. This occurs in an air-circulating oven at 340 °C for 15 h to 20 h. Then, the fibers are immersed into a coupling agent, which is a certain silane. For different types of matrices, different silane coupling agents are recommended. Now, both chemical and physical bonds are established between the the glass fiber surface and the silane. Then, when the fiber makes contact with the resin, a chemical coupling between fibers and matrix is established [1].
The bond created by the chemical coupling agents enhances the load stress transfer between fibers and matrix. This improves both the tensile strength and the interlaminar shear strength. The degree of improvement relies heavily on the coherence between the coupling agent and the polymer matrix. Besides the stated advantages, higher strength interfaces may reduces energy dissipation. A weaker interface may therefore be advantageous with respect to a strong interface because a higher fracture toughness can be attained [1].

Besides chemical coupling, also mechanical coupling occurs between the fibers and the matrix. Mechanical interlocking occurs because the polymer matrix shrinks more than the fibers during the curing process. This shrinking is up to 10x larger [1]. As a result, residual stresses will form around and in the fiber. While this is favorable for the stress transfer between fibers and matrix, at high temperatures or at high loading, the mechanical locking may reduce. When this happens, micro cracks may form which reduces the mechanical properties of the composite. Also, moisture and other reactive fluids may amass around the fibers and cause deterioration in fiber properties.

5.6.2 Carbon fibers

The surfaces of carbon fibers are chemically inactive. Therefore, they must be treated in order to realize a chemical bonding with the polymer matrix [1]. Another effect of surface treatment of carbon fibers is that the fiber surface increases. This enlargement of the porous carbon surface increases the amount of bonds which can be formed with the polymer matrix.There are two commercial surface treatments for carbon fibers, namely oxidative and nonoxidative surface treatments [1].
Acidic functional groups are produces at on the carbon fiber surface trough oxidative surface treatments. These acidic functional groups provide a base to which a polymer

resin can create chemical bonds with. Oxidative surface treatments are carried out in an oxygen-containging gas or in a liquid [1].
Nonoxidative surface treatments came in several forms. For example, in one treatment, the surface of the carbon fiber is coated with an organic polymer [1]. This polymer is able to bond with the polymer resin matrix. The coating can happen by electropolymerization. In this process, the carbon fibers are put in an acidic solution of monomers or monomer mixture. The fibers themselves act as electrodes. The monomers are chemically oxidized and attach themselves to the carbon fibers surface.

5.7 Fillers & additives

Adding fillers to polymer matrices mainly reduces costs but can also enhance certain material properties. For polyester and vinyl ester resins, the most common filler is calcium carbonate [1]. Furthermore, clay, mica and, glass microspheres are also used as fillers. Mallick formed a list with of the advantages of adding fillers to polymer matrices:

– Reduce costs
– Increase stiffness modulus
– Reduce mold shrinkage
– Control viscosity
– Produce a smoother surface [1]

Fillers reduce costs because they are less expensive than the matrix resin. However, adding fillers can increase weight up to 30 % [3]. Hence, structures will be heavier when fillers are used.

Examples of additives are pigments, flame retardants, and low profile additives.
Pigments and dyes can be added to polymer resins to change its color. In most cases, the amount of weight added is small compared to the weight of the resin [3]. Hence, pigment and dyes have no significant effect on the weight of the composite. Besides color manipulation, some pigments also change radiation absorption properties, which will increase resistance against weathering [3].
The fire retardant properties of most resins can be improved by adding flame retardants. Flame retardants can be chemically incorporated during the curing, or they can exist as particulates in physical contact with the polymer resin [3]. Whilst the addition of flame retardants may improve fire retardant properties, they also can lower strength, effect the color, and influence weathering properties. Also, viscosity increases with filler content. Due to this, processing might need to be adopted [3].
Low profile additives are added to resins which are susceptible to high shrinkage. High shrinkage occurs in, among other, polyester resins. If low profile additives are added, the shrinkage of the resin can be positively influenced. Most of these low profile additives are thermoplastics [3].

5.8 Gel coats

Get coats are used to give a glossy, protective surface finish to the composite. They are most often used in the hand lay-up processing technique (see reference chp 3.4). In this process, the gel coat is applied to the surface of the mold. Additives can be used to increase the handling properties of the gel coat. The most widely used additives are thixotropic agents [3]. Thixotropy is a time-dependent material property that decreases viscosity of a fluid when a shear stress acts upon the fluid. If the viscosity of the gel coat is too low, it will start dripping in the mold.

A faster hardening time of the gel coats compared to the hardening time of the polymer is desirable for two reasons. First, short cycle times for the molds increase productivity. Secondly, the hardened gel reduces styrene evaporation. This styrene is needed in thermoplastic polymers to realize cross-links(see Section 5.3.1).

Pigments in gel coats can be used to add color and to change radiation absorption properties of the composite [3].

6 Manufacturing process

A lot of manufacturing techniques for composites are available. This section covers a range of manufacturing techniques. These manufacturing techniques are divided into three categories: open mold, closed mold and continuous processes (see Section 6.3,Section 6.4, and Section 6.5 respectively). Also, the difference between thermoset and thermoplastic processing is highlighted.

Mazumdar states that the criteria for selecting a manufacturing process depend on the following requirements:

- Production rate
- Costs
- Performance
- Size and shape [2]

Also, Mazumdar states that there are four major items needed for production:

1. Raw Material
2. Tooling/mold
3. Heat
4. Pressure [2]

With ranging requirements and the variety in processes, the selection of a manufacturing technique is a specialism in itself. Different manufacturing techniques have different criteria and production characteristics. This chapter attempts to give an overview of the most important manufacturing techniques used in the field of civil engineering. The most frequent applied manufacturing techniques in civil engineering are pultrusion [10].

Mazumdar and Kolstein both describe basic steps in the manufacturing processes of composites [2, 3]. Table 4 presents these steps.

Step	Mazumdar	Kolstein
1	Impregnation	Mixing resin and activator
2	Lay-up	Dispensing resin into the mold
3	Consolidation	Curing
4	Solidification	Positioning reinforcement
5	-	Impregnating reinforcement with resin

Table 4: Basic steps in manufacturing processes according to Mazumdar and Kolstein

The steps of Mazumdar and Kolstein cut up the processes in different steps. Mazumdar identifies the impregnation stage were a lamina is formed by mixing fibers and resins together. In the second step, these laminas (or prepregs) are put together to form laminates. Then, the consolidation stage involves the establishment of a connection between the laminas or prepregs. Mazumdar regards this as a very important step since at this step the trapped air between the laminates is removed. The rate of success of this process largely determines the quality of the end product. This is because voids and dry spots will appear in poorly condensed parts. The final step is consolidation, in which the resin hardens. Thermosets need to cure, whilst thermoplastics only need to cool down. Therefore, this is stage is way shorter for thermoplastics than for thermosets.

The division of Kolstein is based on a division of individual elements. Manufacturing processes differ in one or more of these individual elements. Also, different manufacturing processes will have a lot of individual elements in common.
Both process breakdowns have commonalities. It should be noted that Kolstein in his text book only describes manufacturing processes which use thermoset resins, whilst Mazumdar describes processes with both thermoset and thermoplastic resins.

Table 5 presents an overview of common manufacturing processes and a corresponding qualitative indication with respect to the mentioned criteria.

Process	Production rate	Costs	Performance	Size	Shape
Filament winding	Slow to fast	Low to high	High	Small to large	Cylindrical and axisymmetric
Pultrusion	Fast	Low to medium	High (along longitudinal direction)	No restriction on length; small to medium size cross-section	Constant cross-section
Hand lay-up	Slow	High	High	Small to large	Simple to complex
Wet lay-up	Slow	Medium	Medium to high	Medium to large	Simple to complex
Spray-up	Medium to fast	Low	Low	Small to medium	Simple to complex
RTM	Medium	Low to medium	Medium	Small to medium	Simple to complex
SRIM	Fast	Low	Medium	Small to medium	Simple to complex
Compression molding	Fast	Low	Medium	Small to medium	Simple to complex
Stamping	Fast	Medium	Medium	Small to medium	Simple to contoured
Injection molding	Fast	Low	Low to medium	Small	Complex
Roll wrapping	Medium to fast	Low to medium	High	Small to medium	Tabular

Table 5: Overview of common manufacturing processes and selection criteria [2]

Table 6 presents different manufacturing processes require different raw materials.

Process	Raw material input
Filament winding	Continuous fibers with epoxy and polyester resins
Pultrusion	Continuous fibers, usually with polyester and vinylester resins
Hand(prepreg) lay-up	Prepreg and fabric with epoxy resin
Wet lay-up	Fabric/mat with polyester and epoxy resins
Spray-up	Short fiber with catalyzed resin
RTM	Preform and fabric with vinylester and epoxy
SRIM	Fabric or preform with polyisocyanurate resin
Compression molding	Molded compoound (e.g., SMC,BMC)
Stamping	Fabric impregnated with thermoplastic (tape)
Injection molding	Pallers (short fiber with thermoplastic)
Roll wrapping	Prepregs

Table 6: Overview of different raw material requirements for different manufacturing techniques

6.1 Thermoset and thermoplastic processing

The different nature of thermosets and thermoplastics have a major influence on the manufacturing techniques. Section 5.3 already described the differences between thermosets and thermoplastics. Also, the section briefly introduced the advantages and disadvantages of both resins. Despite that thermoset resins are more common in the field of civil engineering, thermoplastic will be discussed. This is because bio-degradable plastics in general are thermoplastic polymers and these may be covered in a later stage of the thesis. This section gives another brief overview of the advantages and disadvantages of both resins regarding the processing in FRP composites. The following section is based on literature from Mazumdar and Mallick [2, 1].

6.1.1 Advantages and disadvantages of thermoset composites processing

Thermoset resins have several advantages during processing, compared to thermoplastic resins. First of all, it is easier to process thermoset composites. This is because the resin, in general, is liquid at room temperature. The liquid resin is easy to process. Secondly, the fibers are easier to wet. This in turn will reduces the amount of voids and porosities. Thirdly, the processing of thermosets is less energy intensive because less heat and pressure is need during processing. Finally, the tooling systems needed to process thermoset composites are low costs.

Three general disadvantages of thermoset resins with respect to thermoplastic resins are given. First, processing time of thermosets is high compared to thermoplastics. This is because thermosets need to cure and thermoplastics only need to cool down. The cooling down process for thermoplastics may take less than a minute. For thermosets, this may take up to 2 hours [2]. Secondly, thermosets cannot be remolded once cured. Last, closely related to the second disadvantage, is that thermoset composites are hard to recycle.

6.1.2 Advantages and disadvantages of thermoplastic composites processing

Thermoplastic resins have several advantages during processing, compared to thermoplastic resins. First, the process cycle time is very short in general. This is because no time is needed for curing, in which chemical reactions take place. Secondly, thermoplastics can be reshaped and remodeled when sufficient heat and pressure is applied. Last, which is related to the second advantage, thermoplastics are easier to recycle with respect of thermoset resins.

Two general disadvantages of thermoplastic resins with respect to thermoset resins are given. This mainly exists because thermoplastics are solid at room temperature. First, they require heavy tooling for processing. Also, these tools are relatively very expensive. As an example, Mallick states that the typical tooling cost in the injection molding process is $50,000, compared to a mandrel used in the filament winding process costs less than $500. Lastly, thermoplastic resins are not easy to process. Heat and pressure is need to form and model the resin.

6.2 Molds

The quality of the mold influences the quality of the fabricated part and is an important object in the manufacturing processes, not to be overlooked. Mazumdar states several mold design criteria:

1. Shrinkage allowance
2. Coefficient of thermal expansion of tool material and end product
3. Stiffness of the mold
4. Surface finish quality
5. Draft and Corner Radii [2]

A problem faced with the design of the mold and the part itself is shrinkage. Thermoset resins may reduce in volume up to 8 % [3]. The curing process for thermoset resins is an exothermic reaction: energy is released in the form of heat. Hence, during curing, the part warms up. If the cooling is uneven, residual stresses may form in the produced part. This happens when the mold or the part expands much faster or slower than the other. So, an important parameter in the design of molds is the coefficient of thermal expansion (CTE). The CTE of the mold and the fabricated part should match closely [2]. This effect is not huge when the resin cures at room temperature. Also, the geometry of the produced part is set within certain allowances. The mold needs to be designed in such way that the fabricated part complies with these allowances.

Stiffness of the mold is important due to various reasons. One of them is the size of the to be produced part. If larger parts are manufactured, the dimensional stability of the mold itself becomes increasingly important. Molds for large parts can be seen as structures themselves. For example, the production of offshore windmill blades require huge molds [13]. Another aspect is that they need to be stiff enough so their geometry does not changes over large ranging temperatures or pressures. If the mold is not stiff enough, this may cause distortions in the part because the mold itself deforms due to the temperature and pressure changes [2].

If large series of parts need to be fabricated, the mold has to be wear resistant. If the geometry of the mold changes due to abrasion when the parts are released it will deteriorate.

Then, less parts per mold can be produced. This may heavily influences costs, since the mold often contributes significantly to the total costs [13].

In areas like the automotive and the marine industry, a high surface quality is desired. This surface finish relies on the surface finish quality of the tool [2].

The draft and corner radii of the mold should be designed carefully in order to increase resin flow, reduce warpage, and to decrease diffuclty in realsing the part of the mold. Mazumdar suggest to incorporate a 1° draft angle for vertical surfaces [2]. Also, he recommends a minimum inside corner radii of 0.2 cm and a minimum outside corner radii of 0.15 cm in order to avoid sharp corners in the mold and the part. This will both improve the resin flow around the corners and it will make the removal of the part from the mold easier.

In general, molds can be divided into three types: open molds, closed molds and continuous processes [3]. Also, a differentiation between thermoset and thermoplastic molds can be made since the range of needed pressures and temperatures differ for the two types of resins [2]. A big disadvantage of open mold processes is that styrene is released during production. This is considered hazardous to health [27]. Also, as opposed to closed molds, only one side of the part can have a high surface finish quality in open molds.

6.3 Thermoset open mold processes

The manufacturing processes described here are mainly based on the literature of Mazumdar [2], who gives a wide range of extensively described manufacturing techniques in his book *Composites Manufacturing: Materials, Product, and Process Engineering*. Additionally, information from Kolstein [3] is used as well. Corresponding raw material input is presented in Table 6.

6.3.1 Wet lay-up

There are two types of hand-lamination process, one of them is the wet lay-up process. This is the most elementary technique.

In an open mold, a layer of release agent is applied. This makes it easy to remove the part once cured. If a high quality surface finish is desired, a gel coat may be applied. This gel coat needs to harden before the reinforcing layers are placed. When the gel coat is hardened, a layer of reinforcement is applied. The layer is then impregnated with resin and the surface is distributed with the help of a roller. The last step is repeated until the required thickness is achieved. If a sandwich construction is manufactured, a core material (see Section 5.5) is applied if the skin has reached the required thickness. Then, on this core, the other skin is made in a similar way. A good adhesion between the core and the skin is important to establish, which can be done with resin or chemical compounds. If the laminate, or sandwich is construction, is complete, it is cured at either room temperature or at an elevated temperature.

The wet lay-up has several advantages. First, the capital investment costs are very low. The used equipment is low-tech. Second, the process is simple to execute and all kinds of fiber material can be selected and processed in every desired direction. Also, this technique may produces prototypes which are low costs since a simple mold may be used to fabricate the prototype.

However, the wet lay-up processes is very labor intensive, which can make labor costs very high. Because of the manual influence, geometry and quality from different parts may vary. Also, this manufacturing process is not suitable to produce high fiber volume fraction parts. Lastly, the process is not a clean one.

This production processes is often applied to make boats, wind-mill blades, storage tanks, and swimming pools [2].

6.3.2 Prepreg layup

The other hand-lamination process is the prepreg layup. Prepregs are described in 6.3.2.

Working with prepregs works in the following way. First, the prepreg is removed from the refrigerator and stored at room temperature to get it out of its B-stage. Now, the prepreg is workable and it is cut in the desired size and fiber orientation. Then, the mold is prepared by applying a release agent. The prepreg is covered with a backing paper so it does not stick to other surfaces. This backing paper is removed and the prepreg is placed in the mold. This is repeated until the thickness is achieved. With a roller the trapped air between the prepregs is removed after the placement of each prepreg. When the part in the mold is done, a vacuum bagging arrangement is made, sealing the part. Then, the part, including the vacuum bagging arrangement, are placed into a autoclave to cure. Then, a cycle time for pressure and temperature is installed for the autoclave. When the process is finished, the vacuum bag is removed and the fabricated part is ready.

A big advantage of the prepreg lay-up process is that allows production of high fiber volume faction composites. The fiber volume fraction can be more than 60 %. This results are very strong and stiff composite parts. Also, different levels of part complexity can be manufactured with ease. The process is very suitable for the production of prototype parts. While tooling costs are low, the process does require an expensive autoclave.

A limitation of the process, just as with wet lay-up, is the labor intensive nature of the process. Therefore it is not suitable a high-volume of the parts is needed. The amount of manual actions makes it difficult to maintain accurate fiber orientations. It is hard to remove all the trapped air between the prepregs. Also, warpage and distortions make their way into the part easily. Finally, prepregs are expensive, which makes parts manufactured by this process expensive.

This process is used a lot in the aerospace industry and for the production of prototype parts. Examples are wing structures, radomes, yacht parts, and sporting goods [2].

6.3.3 Spray-up processes

In spray-up processes, the thickness of the laminate is acquired by spraying up a mixture of resin, catalyst and chopped fibers. This can be done manual with a spray gun. Or, it can be done with a robot spray gun. This process is less labor intensive, especially when a robot is used.

For the production of a part by spray-up, first the mold is prepared to ease the demolding. This is done by waxing the mold and polish it. Then, a gel coat is applied. After the gel coat hardened, a barrier coat is applied. This barrier coat prevents that fibers affect the gel coat surface. Then, the part is oven cured. When the curing is done, the resin can be applied. With a spray gun, a mixture of resin, catalyst, and chopped fibers is sprayed on the mold surface. When a layer is applied, the entrapped air is removed with a roller. Also, rolling distributes the mixture uniformly over the mold surface. If a sandwich structure is created, a core may be placed and another layer can be sprayed on the core material. When finished, the part is cured in an oven. In contrary to prepreg processing, the parts need to be finished more intensely and the parts require a solid quality control.

A big advantage of the spray-up process is that small to large parts can be produced cheap. This is because low-costs tooling as well as low-cost material systems are used. The manufacturing technique is also considered suitable for small to medium ranging volume parts.

The spray-up process is bound to some limitations. For instance, the process does not lend itself well for the manufacturing of parts which need high structural requirements. This is because only chopped strands can be processes into the composite part. Also, the distribution of the fibers and resin, the local fiber volume fraction, is hard to control. When doing manual spray-up, this highly depends on the skill of the operator. Because of the spraying nature of the process, it is not suitable if high dimensional accuracy and process repeatability are desired.

Spray-up becomes a suitable option when strength is not considered crucial. Examples of commercial products manufactured by this process are bathtubs, swanning pools, boat hulls, storage tanks, duct and air handling equipment, and furniture components such as seatings [2].

6.3.4 Filament Winding

In filament winding, impregnated fibers are wound over a rotating mandrel. A machine may move along an axis and wound the fibers under an angle on the mandrel. This process is very suitable to produce tubular parts.

The production process begins with setting up a spools with yarn. From this spools, fibers are taken and guided through pins. The fibers go trough a resin bath. Then the impregnated fibers are wounded on the mandrel under tension. This mandrel is coated with a release agent. Also, a gel can be applied beforehand, if desired. Then, the mandrel starts spinning and the payout eye, which guides the impregnated yarns, moves over a rail. When the required thickness is met, a Teflon-coated bleeder or shrink tape can be applied on the top of the outer layer if a smooth surface finish is desired. The mandrel, containing the manufactured part, is then moved to a room where the resin can cure. After curing, the mandrel is removed. In some application, the mandrel is not removed. The mandrel then becomes part of the structure.

Filament winding is for some applications, such as pressure vessels, the only method which produces a part which is both relatively cheap but still high-performance. The low costs are because the process utilizes cheap tools and raw materials. Another advantage is that the process can be automated.

With the filament winding process, one disadvantage is that only closed and convex structures can be produced. Also, the maximum fiber volume fraction which can be obtained with this process is 60 %. Last, the fiber distribution and resin content will vary throughout the thickness of the laminate.

Filament winding is used to produce tabular structures, pressure vessels, pipes, rocket motor casings, chemical storage tanks, and rocket launch tubes [2].

6.4 Thermoset closed mold processes

6.4.1 Resin Transfer Molding (RTM)

With the resin transfer molding technique, woven fabric is placed in a mold, which can be enclosed by a bag; then, the bag or mold is infused with resin in order to create a composite. It is often used to create more complex composites.

First, a mold cavity is created. In this mold cavity, continuous fibers or mats are placed. The resin is than infused. The quality of the product is greatly influenced by the ability of the liquid resin to reach all the designated places [15]. To assisst the distribution of resin, a vacuum may be applied to the mold or bag in order to reach narrow spaces. In this case, the manufacturing process is also called Vacuum assisted resin transfer molding (VARTM).

6.5 Thermoset continuous processes

6.5.1 Pultrusion

Pultrusion is a contraction of the words ”to pull” and ”extrusion”: instead of pushing a material through a mold, it is is pulled through a mold. The pultrusion process is very suitable for manufacturing long elements cross-sections such as beams and rods. It is therefore commonly used for construction elements in the civil engineering industry.

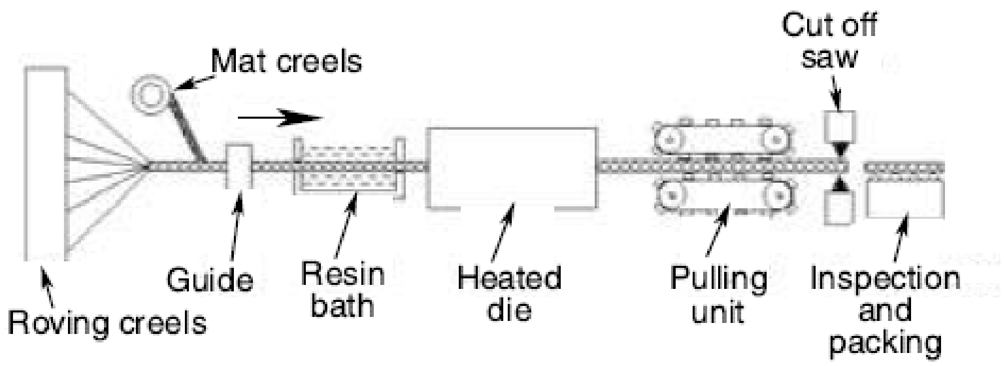

Figure 14: Schematization of the pultrusion process [15]

Figure 14 illustrates a schematization of the pultrusion process [15]. Fibers and mats, often mounted on spools, are pulled through a resin bath. A guide makes sure that the filaments are properly arranged. Once the filaments are impregnated, the resin is heated and molded through a heating mold. The product which leaves the mold is a solidified cross-section, which is then cut off at the desired element length.

The fiber orientation angle is limited in the pultrusion process. Individual filaments can only by asserted in the pultrusion direction, which is 0° [15]. However, transversal stiffness can be added by introducing woven mats. The fiber content of pultruded elements can

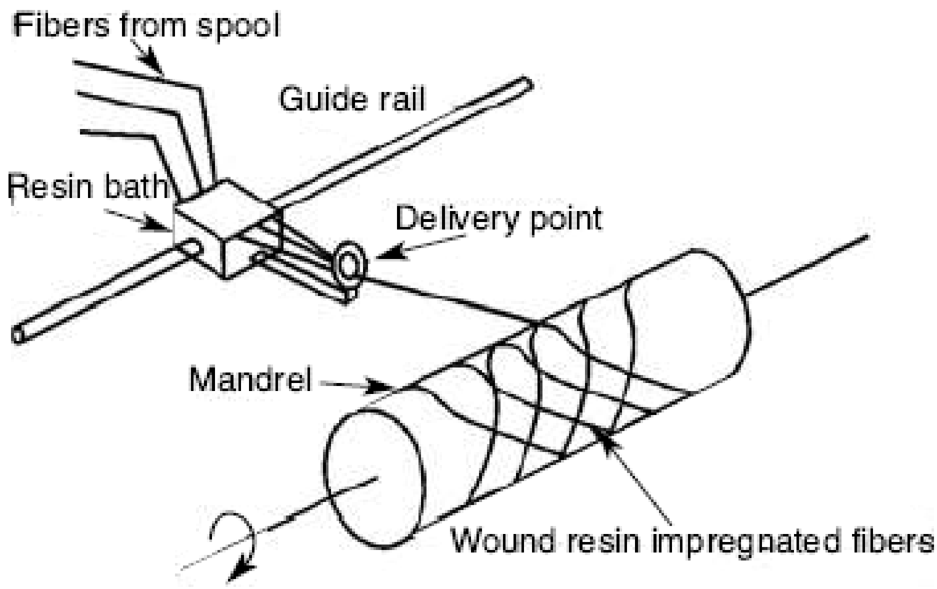

Figure 15: Illustration of the filament winding process [15]

be up to 70 %, containing roving mat ratio of 0.6 to 1.16 [1]. It must be noted that this range dates from a journal from 1986.

6.5.2 Continuous filament winding

Filament winding is the process of winding impregnated filaments on a mandrel. This technique is very usable for manufacturing long circular elements.

Figure 15 illustrates the filament winding process [15]. The fibers are mounted on a spool and then guided to the mandrel through a resin bath. The mandrel spins, and therefore the fibers gets winded around the mandrel. Proper placement of the fibers on the mandrel are ensured by guiding the fibers trough a delivery point. The resin bath and delivery point are mounted on a guide rail, and by moving them continuously all of the mandrel gets covered by impregnated fibers, eventually forming the FRP element. Fiber angle can be adjusted by determining the diameter of the mandrel and the velocity of the delivery point. When the fibers are placed upon the mandrel, the FRP product is cured either at room temperature or in an oven. When the product is finished, the composite part is removed from the mandrel [15].

6.6 List of suppliers, contractors and experts

This section presents lists of suppliers, contractors and experts fur further references.

	Company name	Website	Description
Product suppliers	Enviroplast	www.enviroplast.nl	Recycled plastics
	Aquamore	www.aquamore.info	DIY-docks
	Polyproducts BV	www.polyproducts.nl/en/	FRP specialist
	Creative Pultrusions	www.creativepultrusions.com	Pultrusions products
	Strongwell	www.strongwell.com	Pultrusion products
	Fiberline	www.fiberline.com	Pultrusion products
Contractors	MOCS	www.mocs.nl	FRP Engineering consultant
	FiberCore-Europe	www.fibercore-europe.com	FRP specialist
	Trelleborg	www.trelleborg.com	Polymer engineering

Table 7: Overview of several companies in the FRP construction field

7 Structural components in FRP

This section explores structural elements made of composite and shows how the properties of composites can be determined. For the structural design of FRP composites is refered to Section 8.

7.1 Beams

Beams are common and important structural parts. When beams are made of FRP, a few design challenges arise. The most important design issues are to find an optimal beam cross-section which improves transverse stiffness, and the realization of joints and connections of the beams to the rest of the structure [3].

Several items should be regarded when optimizing the cross section of a beam. When applying FRP beams and girders in civil engineering structures, most often the size of elements is determined by deformation restrictions as opposed to strength limits [3]. An I-beam or W-beam lends its stiffness mainly trough its flanges. The web is prone to twisting and buckling, which is called the slender column effect. This problem can be overcome in several ways. For instance, by adjusting the distance between the beams or by adding stiffeners to the beams.

Strongwell, an FRP pultrusion production company, did a lot of research in optimizing the cross section of an FRP beam. The result is a double webbed, internally flanged beam with both glass- and carbon fibers, see Figure 16 [28]. The beams have a flexural modulus which is larger than 6000 ksi (41.37 GPa, steel has a flexural modulus of 180 GPa to 200 GPa).

Figure 16: EXTREN DWB, produced by Strongwell

Kolstein investigated company reports and states that the best method of fastening of beams is"a combination of mechanical fasteners and adhesive bonding" [3]. In Section 9 this topic is further elaborated.

Strongwell also made a design manual with respect to the products they manufacture. In one section, they present the flexural members they manufacture, accompanied with load tables and calculation sheets in order to select suitable members given the loads which act upon the members [29].

7.2 Trusses

Trusses can be very effective in reaching large spans with a minimal material volume. Hence, they are applied a lot in bridge structures. Trusses are designed in such way that only axial forces work on the members. This may prove very valuable for FRP composites because of their high axial strength. Also, coping with shear forces in composites is a problem in general due to the relative low resistance to shear stresses. High shear stresses may lead to delamination of the composite.

When designing a truss, the diagonal members may be subject to tension or compression. Materials most often have either a higher tensile strength or a compressive strength and those properties should be used to their advantage. For FRP composites, the fibers have better tensile strength properties with respect to their compressive strength, but the resin material posses a better compressive strength with respect to its tensile strength [3]. This should be kept in mind when designing a composite structure.

7.3 Decks

FRP bridge decks come in a wide variety.
The dead weight of several bridge lie around $1\,\mathrm{kN/m^2}$ [3].

7.4 Sandwich panels

Sandwich panels consist of two outer composite plates and an internal core material, see also Section 5.5. This is a very effective construction if the weight of a beam needs to be reduced while its bending resistance capacities largely remain unaltered.

A formula for determining the bending stiffness per unit of width of a sandwich panel is given by Mallick [1]:

$$(EI)_b = E_s \frac{bt^3}{6} + 2bE_s t \left(\frac{d+t}{2}\right)^2 + E_c \frac{bd^3}{12} \tag{1}$$

With:

E_s : elasticity modulus of the skin material
E_c : elasticity modulus of the core material ($E_c \leq\leq E_s$)
b : beam width
t : skinn thickness
d : core thickness

Nijssen gives a formula for the shear stress in a beam because it is likely that the deflection due to shear stresses has a significant contribution compared to only the deflection due to bending [13]:

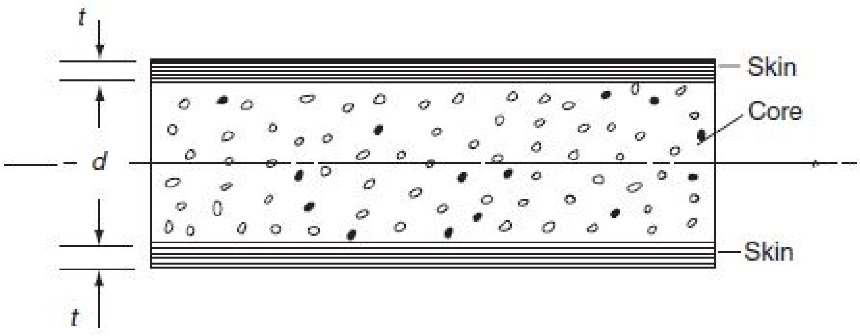

Figure 17: Parameters of a sandwich panel [1]

$$\tau = \frac{Q}{d + t/2}\left(E_s \frac{t(d + t/2)}{2} + E_c \frac{1}{2}\left(\frac{d}{2} - z\right)\left(\frac{d}{2} + z\right)\right) \tag{2}$$

Where:

Q : transversal force in
z : perpendicular distance to the neutral axis

This shear stress can be used to check the cross sections as presented in Section 8.3.

7.5 Piles

Back in 2001, Iskandar et al. named several barriers which had to be overcome in order for FRP to become accepted in the construction industry.

- FRP piling needs to be cost-competitive on a life-cycle basis
- Mechanical and physical properties should be defined
- Long-term performance should be verified under field conditions
- Design methods for predicting driveability and capacity should be developed
- Design and testing standards should be developed
- A portion of piles should be instrumented, installed, load tested, and monitored [17]

7.5.1 Composite pile types

Recently, in 2016, Zyka and Mohajerani reflected and elaborated upon these items [4]. In their article, they present five different types of composite piles which seem suitable as alternatives for load-bearing applications or fenders:

- Concrete filled and hollow FRP piles
- Steel pipe plastic core
- Reinforced plastic matrix piles
- Fiberglass pultruded piles
- Fiberglass reinforced plastic piles

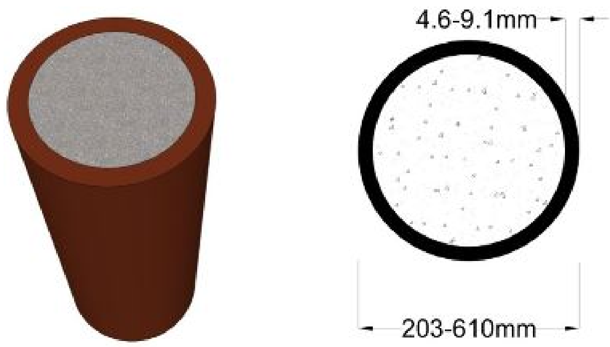

Figure 18: Concrete pile[4]

Concrete filled FRP piles have a shell of FRP and are filled with concrete. The piles are also installed without a concrete core. The concrete core bears the compressive loads, while the FRP pile bears the tension forces due to the confinement of the concrete. The concrete also increases the resistance to local buckling. It is the combination of excellent compressive bearing properties and high tensile stress resistance which makes this pile suitable for load bearing functions.
The filling may be done either before driving or when the hollow section is installed. During driving, the foot of the pile rests on a steel plate.
A problem during installation may rise with this pile type [17]. First, the concrete core may be de-bondend from the pile section. This results in a poor transfer of axial driving forces which may lead to a poor installation of the pile. The bonding between the concrete core and the hollow pipe section may be improved by adding an epoxy resin.

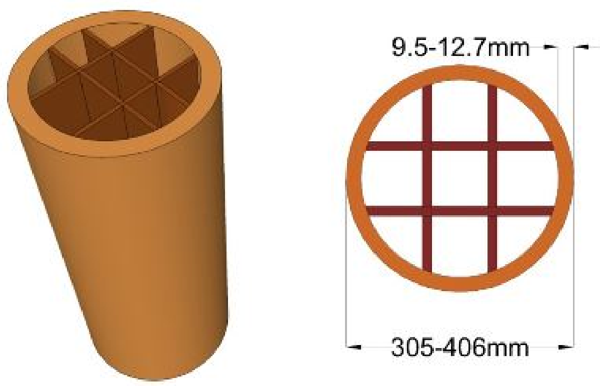

Figure 19: Fiberglass pultruded piles[4]

Fiberglass pultruded piles exists of a high-density polyethylene shell and an internal grid of flanges. These flanges provide structural strength and decreases the deflections when under a load. The voids may be filled with a foam or plastic lumber. Fiberglass pultruded piles are used as fenders in marine environments. This pile has not a lot of resistance to axial and lateral loads and is therefore unsuitable for load bearing functions.

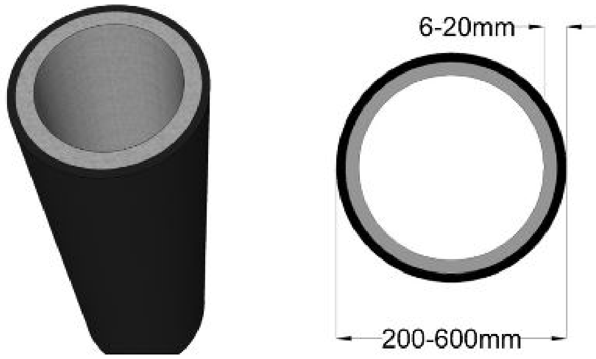

Figure 20: Steel core plastic piles[4]

Composite steel core piles are steel piles which are surrounded by a plastic shell. The steel core bears the axial loads and the plastic shell protects the core against corrosion. Research regarding plastic shells is done because cathodic protection and coats are considered dangerous to the marine environment [4]. The plastic shell can be manufactured from recycled plastic and may contain glass fiber flakes. Advantages of this pile type are a high tensile stress, less damage sensitive during installation and the possibility to adjust the pile length during installation.
After installation, problems with the pile may arise. After one year, cracks may appear in the plastic [4]. The steel core pile may than come in contact with the salt water, leading to corrosion. This problem may be prevented by only applying the plastic core on the steel area which is in contact with the water. This reduces the stresses in the plastic shell, which resolves the problem.

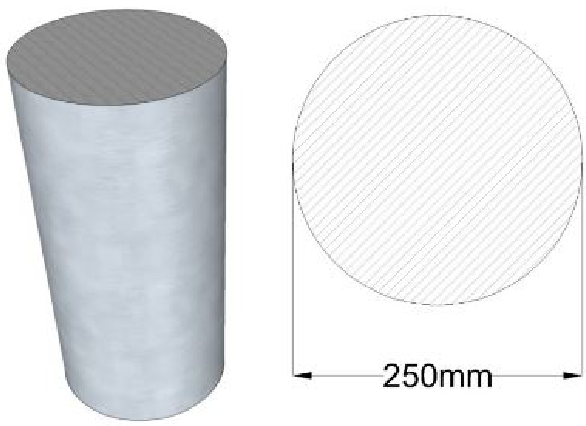

Figure 21: Fiberglass reinforced plastic piles[4]

Fiberglass reinforced plastic piles is a pile which consists of a polymer matrix mixed with random fiberglass reinforcements. This pile is used for fender applications. In a research, a pile with a diameter of 250 mm and a length of 7.5 m was tested and a Young's Modulus of 0.37 GPa was found [4]. This makes the pile unsuitable for load bearing functions.

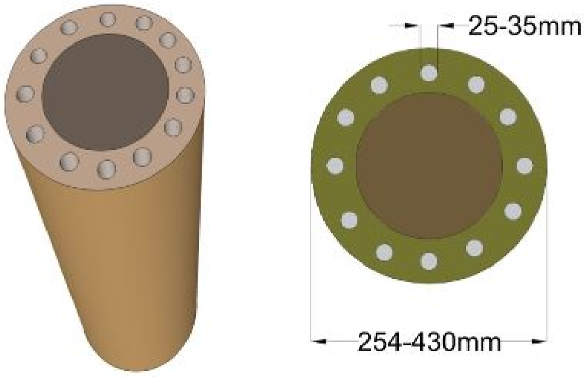

Figure 22: Reinforced plastic matrix piles, or SRP[4]

Reinforced plastic matrix piles, also called structurally reinforced plastic (SRP), are reinforced in their core instead of consisting of two different shells or a shell/core combination. The plastic most often consist of recycled plastic and the reinforcement are either steel or FRP rods. The piles might be fully recyclable when used in combination with FRP rods. The piles can be protected with chemical treatments and stay well protected against UV light. Usually, this pile functions as a fender, but piles with a diameter of 305 mm can withstand up to 20 tonnes of working load [4].
The main problems of this pile are the de-bonding between the plastic core and the reinforcement bars and relatively high creep rates. Also, the pile is very flexible, which results in big deflections during loading. However, the piles are still suitable for load-bearing applications.

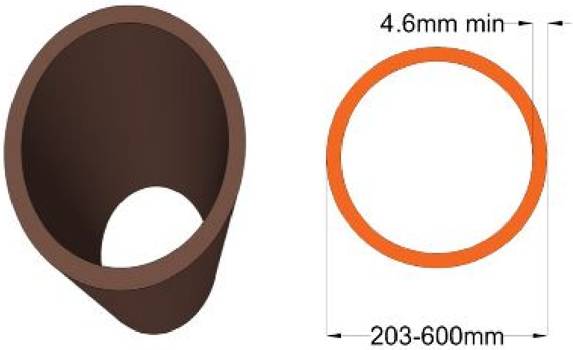

Figure 23: Fiberglass reinforced plastic hollow piles[4]

Hollow FRP piles are hollow shells of FRP. The piles can be manufactured with pultrusion, filament winding or a resin transfer molding process.
In a research, the structural performance of glass and carbon FRP piles were tested. The test took place in a soft undrained clay. The hollow FRP piles had greater adheasion with the surrounding clay compared to steel. The axial load capacity was in about similar to that of steel. A less desired property was a larger pile head deflection of the hollow FRP piles compared to those of steel.

Piles produced by Pearson Pilings have an estimated life spans of more than 100 years, not vulnerable to corrosion and a Young's Modulus of 28 GPa [4]. However, a water aborption of up to 25 % might be possible. This is undesirable when deploying this pile in a marine environment with a load bearing function. CMI has developed the “UltraComposite” pile, which has a diameter of 457.2 mm and an ultimate compressive strength of 165.4 MPa.

7.5.2 Available piles in the market

There are some FRP piles commercially available.
The SEAPILE, is developed by Bedford Technolog’s.

7.5.3 Costs

Table 8 presents costs per meter founded by Zyka et al. for different composite pile types. As can be seen, the costs per meter of fiberglass reinforced plastic piles is more than twice that of hollow FRP piles. Hence, the cost range varies greatly.
The SEAPILE, manufactured by Bedford Technology’s, is initially more expensive than wooden piles. However, their maintenance is very low. After six years, the costs of the SEAPILE are the same as a traditional wooden pile. After this period, the costs of the wooden pile increases exponentially, whilst expenses for the SEAPILE remain low [4].

Composite pile type	Costs [$AUD/m]	Diameter [mm]	Wall thickness [mm]	Length [m]
Concrete filled FRP pile	195	203 to 610	4.6 to 9.1	32
Composite steel pipe core pile	320	23	20 tonnes for 300 mm	
Plastic shell		200 to 600		
Steel core			6 to 20	
Reinforced plastic matrix pile	380	254 to 430		
Fiberglass pultruded pile	N/A	305 to 406	9.5 to 12.7	
Fiberglass reinforced plastic piles	390	250	N/A	7 5
Hollow FRP piles	165	203.2 to 600	4.6	up to 22

Table 8: Overview composites from Zyka et al. [4]

Pile type	Cross-sectional area [mm^2]	Density [kg/m^3]	Young’s Modulus [GPa]
315 mm diameter prestressed concrete pile	77,900	2406	34.5
340 mm diameter steel pipe pile (9.5 mm wall thickness)	9,900	7849	200
356 mm diameter timber pile	99,500	815	13.8
325 mm diameter concrete-filled FRP pile	83,000	2240	31
254 mm diameter steel pile core pile	11,300	7849	200
406 mm diameter SRP pile (with FRP tendons)	129,500	770	5.4
356 mm diameter hollow FRP piles (13 mm wall thickness)	14,000	1927	23

Table 9: Different piles and their properties [4]

7.5.4 Design of composite piles

The design of composite piles requires attention to certain special areas compared to traditional concrete, steel and wooden piles. The main focus areas when designing piles are driveability, axial loading, lateral loading, and long-term structural capacity [4]. Zyka and Mohajerani reviewed these areas for FRP concrete filled piles, reinforced plastic matrix piles and hollow FRP shell piles. This review is based on research articles and literature.
Installation of piles

7.5.5 FRP pile installation

For technical feasibility, an implementation design has to be implemented to give if a complete assessment regarding the technical feasibility is made.

Pile installation techniques can be divided in two general categories: soil displaced techniques and soil removal techniques. Three common methods for the installation of the pile:

- Pile driving
- Vibrating techniques
- Drilling

Concrete piles can also be cast in-situ, like the vibro-pile. However, this is not applicable for FRP piles: during production processes, hazardous substances may be released (for instance, when manufacturing epoxies [15]). Therefore, they need to be manufactured in controlled (e.g. ventilated) rooms. This indicates that creating in-situ piles of plastic, in a non-controlled environment, may cause harm to the environment.

[30] With the drilling technique, the surrounding soil gets affected during pile installation which results in a decrease of bearing capacity. Driving and vibrating installation techniques displace the soil, making it more packed and, hence, increasing the strength and stiffness of the soil.

Of these piles, the hollow FRP pile seems the most feasible option, due to its light weight and low costs, but still excellent load bearing capacities [31].

FRP piles come with some challenges: they may fail due to low flexural resistance and buckling with conventional head driving [32]. Sakr recommends different options such as toe driving (however, Guades says that the research says that this is only viable for sand and not for clay [31]) or vibratory hammers.

Impedance is important for pile driving efficiency: also called the dynamic stiffness, it indicates how well the pile is able to transfer the energy from the hammer blow to the head of the pile, to the foot of the pile, and overcome the soil resistance there. The formula for the impedance is: Z $= \rho Ac = \sqrt{\rho E}A$. Hence, increasing the E modulus or the density of the pile has hardly any impact; increasing the pile area will scale the costs linearly [31]. Therefore Guades concludes that improving impedance by working on material properties such as A, density, and E is not the optimal solution.

Guades states that research regarding damage parameters such as impact energies and number of impacts need to be researched; also, as of 2012 that all research regarding fatigue properties of FRP or in the automotive and aerospace industries but not yet conducted for FRP piles [31]. The most important thing he says that needs to be researched is a study on axial impact behavior of hollow FRP piles [31].

Mirmiran found that hollow FRP piles were only able to be loaded 40 % to 50 % compared to FRP piles filled with concrete [16]. This may be due to buckling and rupture tendencies of the FRP [31]. Ashford et al. found, in a theoretical study, that the bearing capacity of FRP piles was limited to 65 % to 75 % (at refusal) related to the bearing capacity of other investigated piles (concrete, steel, concrete filled GFRP pile, and a plastic encased steel pipe) [33].

Figure 24: Damage after driving on pile head [16]

Iskander et al found that hollow FRP piles can be driven to depth with reasonable load bearing capacity in a theoretical study using WEAP [17]. The high load-bearing piles in the study had a length of 27 m. The geo-technical conditions of a typical Manhattan soil profile were taken as illustrated in Figure 25.[17]. The driven depth (18m) and the pile length (27m) correspond to the intended piles with the decisive load case for the jetty (26m and 16 m respectively).

High frequencies are more damped by the surrounding soil than low frequencies[34]. CUR also states that in cohesive soils, the cohesion makes the soil particles stick together so the soil will not liquidize. They state that the ideal soil for vibrating is fine, loosely packed, saturated sand.

The principle of vibrating is to liquidize the surrounding soil to reduce friction resistance. Then, a lower normal force is required to push the pile into the ground[34].

Clear installation guidelines miss for hollow FRP piles and researchers are trying to provide these in order to make hollow FRP piles commercially attractive [4]. Topics which need to be explored regarding hollow FRP piles are: “the effect of cyclic horizontal deflection on the lateral of composite piles” [4], “studies related to the determination of impact strength and damage characterisation” with the most important one being a “study on the axial impact behavior of hollow FRP piles” [31].

Conclusion pile driving: hollow FRP pile

We can conclude the following:

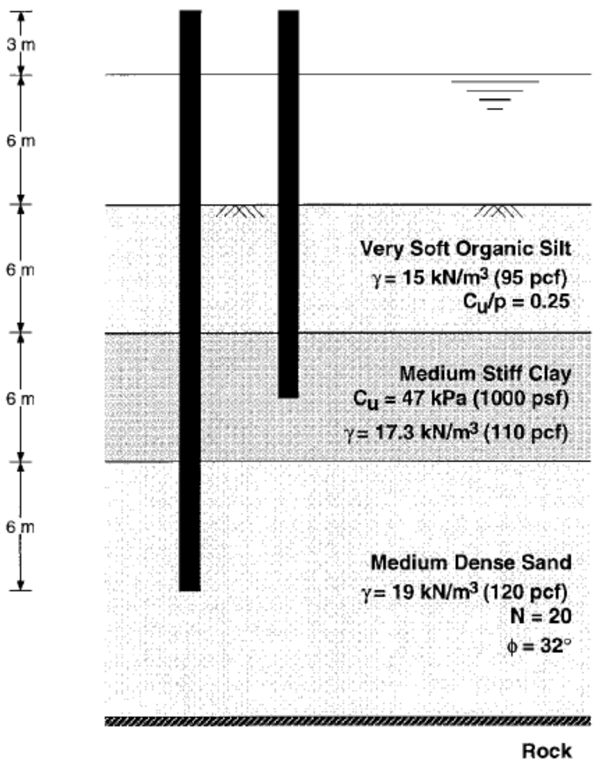

Figure 25: Soil profile in the theoretical investigation of Iskander [17]

- Of the different commercially available piles, the hollow FRP pile seems the most feasible when regarding load bearing capacity and cost efficiency
- Theoretical research utilizing WEAP suggested that, with pile and geotechnical conditions approximate to the design situation, hollow FRP can be driven to depth with reasonable bearing capacity.
- Challenges to overcome regarding driving of hollow FRP piles is the low impedance of these piles. Increasing the impedance by adjusting material properties or pile dimensions is not an optimum solution. This solution probably lies in the adjustment of installation techniques. (such as tapered piles. The effectiveness of this method however, is only in granular non-cohesive soils).
- No systematic damage resistance and axial fatigue studies have been conducted for hollow FRP piles
- The research regarding pile installation is focusing mainly on pile driving

Taking these conclusions into account, the following available options seem reasonable to assess the feasibility of the installation of the FRP piles:

- Conduct a pile driving analysis and design a pile cushion
- Conduct a pile vibration analysis
- Further research the possibility of drilled piles

8 Structural design in FRP

In this section, different design guidelines are presented and the most prevailing one in The Netherlands, the CUR 96, is further elaborated.

A laminate is build up of several laminas. The fiber orientation, fiber content and other properties may vary between laminas, which is the beauty of composites. The general idea is to first determine the properties of laminas in their principal directions. That is, the main fiber direction in the lamina. Then, with the classical laminate theory, the properties of laminates can be determined. Mallick and Nijhof have written excellent textbooks on the mechanics of FRP composites [1, 23]. The main design guidelines in The Netherlands with respect to FRP is the CUR 96. This guideline provides practical design rules for composites [5]. The formulas regarding structural design which are elaborated here

In The Netherlands, the most prevailing design guidelines in the civil engineering sector are presented by the Nederlands Normalisatie Instituut (NEN) and Civieltechnisch Centrum Uitvoering, Research en Regelgeving (CUR). These are based on the Eurocodes. For FRP, a revision of CUR96 in 2016 is available. This design guideline is the most applied guideline for FRP structures in The Netherlands. It encompasses a safety philosophy and practical application guidelines. The structural design of the jetty will be based on CUR96. This chapter elaborates sections in CUR96 which are ought important for the structural design of the jetty. Also, this chapter gives an overview of common structural elements and their commercially available FRP executions.

8.1 Design guidelines

In 2016, the Joint Research Centre of the European Commission highlights the issue that FRP composites are gain market share in the construction industry whilst European construction guidelines are lacking [10]. Therefore, a report named “Prospect for New Guidance in the Design of FRP” was created which functions as a first draft for European construction rules regarding FRP.
An overview of guidelines for engineering FRP application to civil engineering have been developed in several countries:

- EUROCOMP
- CUR96
- BD90/05
- DIBt
- CNR-DET 205/2007
- ACMA
- DIN13121
- BÜB[10]

The CUR 96: Fibre Reinforced Polymers in Civil Load Bearing Structures, is a Dutch design guideline. The CUR 96 bases its design philosophy on the Eurocodes, which are codes set for the construction industry in the European Union. The CUR 96 is mentioned as the first design guideline in the Prospect for New Guidance in the Design of FRP, which may indicate that it is the most comprehensive design guideline in the European Union.

Product manufacturers often have developed their own guidelines, like Storngwell [35]. However, these design guidelines are often limited to the range of products which are produced by the manufacturer.

8.2 Material selection

8.3 CUR Recommendation 96

The CUR-recommendation 96 provides guidelines for designing with FRP constructions in The Netherlands. CUR 96 covers subjects such as the determination of mechanical and physical properties of laminas and laminates, design foundations, inspection and maintenance, durability, and sustainability.

8.3.1 Design philosophy and material properties

The CUR recommends design and calculations according to the limit state design philosophy. These limit states are based on the design philosophy presented by the Eurocodes. There are two limit states, the ultimate limit state (ULS) and the serviceability limit state (SLS). The ULS requirements are related to structural integrity of the constructions. The SLS requirements are related to the serviceability of the construction during its lifetime under characteristic design loads. Requirements include, among others, deflection limits, comfort, settlements, and vibrations. For both limit states, different load cases are formulated according to the NEN-EN 1990 and the NEN-EN 1991.
The limit states are tested by the method of partial factors. Partial factors are used to calculate the design values of resistant components (denoted by R) and load components (denoted by E).

$$R_d = \eta_c * R - k/\gamma_M \tag{3}$$

Where:

R_d : design value of the resistance
R_k : characteristic value of the specific resistance, determined with the characteristic values of the material properties and dimensions
γ_M : partial material factor
η_c : conversion factor

For load cases where multiple loads have assigned different conversion factors, the principle of superposition has to be applied when testing the resistance. Requirements are:

$$E_{d,i} \leq \eta_{c,i} \leq R_{k,i}/(\gamma_M)i \geq 1\text{and} \tag{4}$$

Where:

$E_{d,i}$: design value of part i of the occurring load case
$R_{k,i}$: part of the characteristic value of the specific resistant which is used by part i of the load
$\eta_{c,i}$: conversion factor for part i of the load

The design value of a material property has to be calculated with the formula:

$$X_d = \eta_c * X/(\gamma_M) \tag{5}$$

Where:

X_d : design value of a material property
X : X_k or X_n
X_k : characteristic value of a material property
X_n : nominal value of a material property

For the partial material factor:

$$\gamma_M = \gamma_{M1} * \gamma_{M2} \tag{6}$$

Where:

γ_M : partial material factor for the specific resistance. This value is dependent on test results
γ_{M1} : partial material factor coupled to the geometric deviations
γ_{M2} : partial material factor which discounts uncertainties regarding strength properties and which is dependable on the spread of material properties

The material factor γ_M takes variance into account for material properties. The conversion factor η_c discounts anticipated effect of the environment, duration of loading and cyclic loading on the material properties of FRP.
The actual values of these material factors can be found in the [5]. Also, material factors for glue connections have been specially determined.

The CUR 96 gives target values and characteristic values for material properties. Target values are typical values which are technically feasible but which have no specific reliability level. These values need to be backed up with laboratory test results. Characteristic values are determined, unless specific otherwise, in one of the following ways:

- The value which occurs at a 5 % exceedance probability if the low value of a material property is disadvantageous
- The value which occurs at a 95 % exceedance probability if the high value of a material property is advantageous

For the Young's Modulus E, the average value may be taken. Target values for material properties are presented in the CUR 96 [5]. For fibers, the density, Poisson ratio, stiffness, strain limit, and yield strength are given for E-glass, R-glass, high strength carbon (HS), high tenacity carbon (HT), intermediate modulus carbon (IM), high modulus carbon (HM). These properties are given for tension in fiber direction, tension lateral to fiber direction, compression in fiber direction, and shear. Also, the thermal expansion coefficient is given.
For resins, target values for the density, Poisson ratio, glass transition temperature, tension- or compression strength, stiffness under tension, strain limit under tension or compression, shear modulus, shear strength, shear strain limit, and thermal expansion coefficient. This is done for three thermoset polymers: polyester, vinyl ester and epoxy.
For core materials, target values for the density, compression strength, shear strength, Young's Modulus, and shear modulus are given of different densities for PUR, PVC, and PMI.

8.3.2 Reference system

The CUR 96 defines reference systems which are presented in Figure 26 for fibers and laminas and in Figure 27 for laminates.

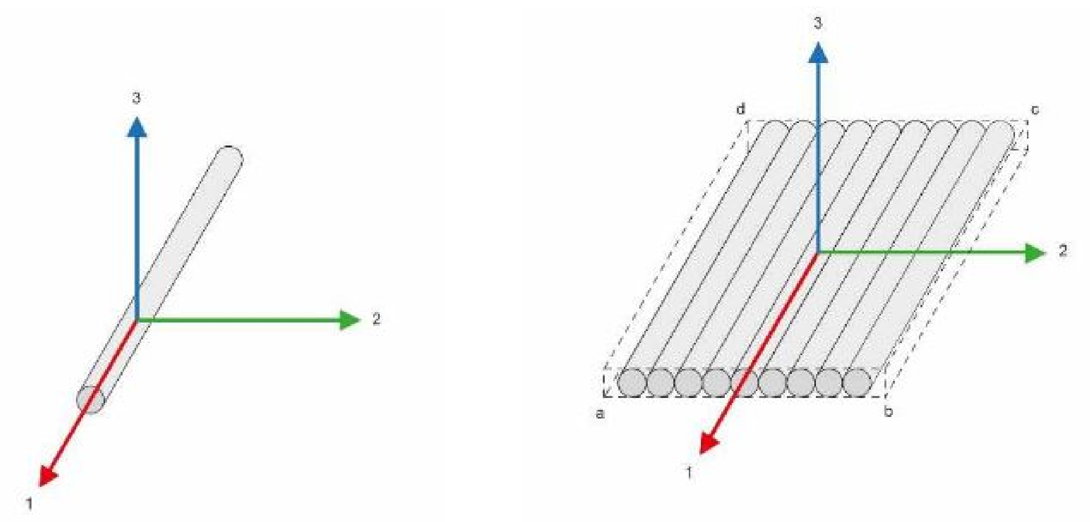

Figure 26: Principal directions for a fiber (left) and a lamina (right) as defined by the CUR96 [5]

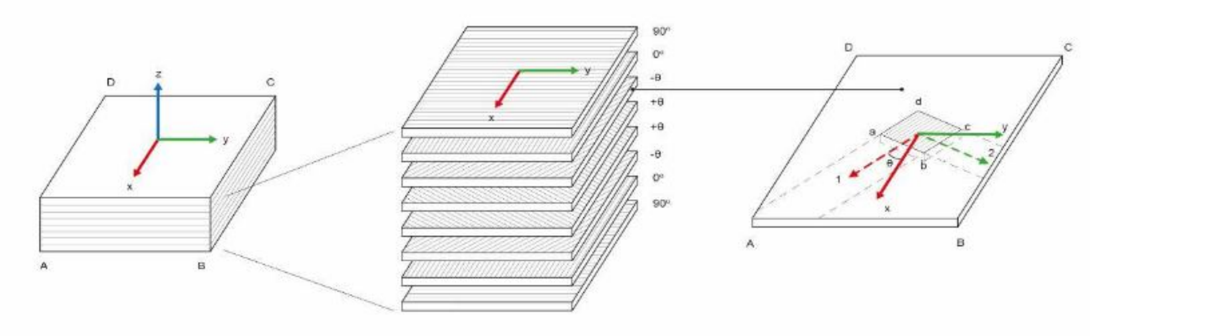

Figure 27: Principal directions for a laminate as defined by the CUR96 [5]

8.3.3 Model assumptions for the determination of mechanical properties of composites

When describing composites, different mechanical processes can be described at different levels. On one hand, at a micro level, interaction between the fiber and the matrix is described. On the other hand, at a macro level, relations between deformation and stresses due to external loads and imposed deformations are made. A lot of mechanics are active. Therefore it is hard to incorporate all of them into a model that represents the properties well. The key is to make good assumptions so modeling will be simplified, but that the model still represents reality suitable for engineering purposes.

Nijhof treats several models which are used to determine the mechanical properties of composites [23]. Nijhof compared the models by plotting the material properties according to different models to the fiber volume fraction. The compared models are the models of Hashin & Shtrikman, Voigt (parallel model), Reuss (serie model), Christensen & Lo, Halpin & Tsai, Tsai & Hahn, and Puck (limit area). Nijhof also states that experiments

in general generate results with lower performance of the composites than predicted by the models. It should be noted that the CUR 96 uses the Halpin & Tsai model with empirical reduction factors. Mallick states that the Halpin Tsai model produces equations that "agree reasonable well with the experimental values for a variety of reinforcement geometries, including fibers, flakes, and ribbons" [1].
The following assumptions are used by Mallick in his presentation of laminar theory:

- Fibers are uniformly distributed throughout the matrix
- Perfect bonding exists between the fibers and the matrix
- The matrix is free of voids
- The applied force is either parallel to or normal to the fiber direction
- The lamina is initially in a stress-free state (i.e., no residual stresses are present in the fibers and the matrix)
- Both fibers and matrix behave as linearly elastic materials [1]

These are used in determining the rule of mixtures and the classical laminate theory (see Section 8.3.4 and Section 8.3.6 respectively).
Further assumptions regarding various topics are presented in the CUR 96. The assumptions are based on requirements set by the Eurocodes and the Dutch national appendix. These include the modeling of joints, interaction between subsoil and structure, and the definition of load cases. The CUR 96 also gives guidelines and assumptions for the schematization of structures, incorporating global and local imperfections, analytic calculations methods, and finite elements methods.

8.3.4 Lamina properties

CUR 96 provides formulas to calculate properties of laminas for UD-laminas, bi-directional laminas and mats. The most important mechanical properties which need to be determined for a lamina are (see Figure 26 for axis definitions) its elasticity modulus in transverse and lateral direction, shear modulus, and Poisson's ratio. For certain standard compositions of E-glass and unsaturated polyester resins, the characteristic values of these properties are provided by the CUR 96 based on fiber volume fraction. It is noted that the highest elasticities can be achieved for UD laminas.
For UD-laminas:

$$
\begin{aligned}
E_1 &= \left[E_R + \left(E_{F1} - E_R\right) V_f\right] \cdot \phi_{UD} \\
E_2 &= \left[\frac{\left(1 + \xi_2 \eta_2 V_f\right)}{\left(1 - \eta_2 V_f\right)} E_R\right] \cdot \phi_{UD} \\
G_{12} &= \left[\frac{\left(1 + \xi_G \eta_G V_f\right)}{\left(1 - \eta_G V_f\right)} G_R\right] \cdot \phi_{UD} \\
\nu_{12} &= \nu_R - \left(\nu_R - \nu_F\right) \cdot V_f \\
\eta_2 &= \frac{\frac{E_{F2}}{E_R} - 1}{\frac{E_{F2}}{E_R} + \xi_2}; \xi_2 = 2 \\
\eta_G &= \frac{\frac{G_F}{G_R} - 1}{\frac{G_F}{G_R} + \xi_G}; \xi_2 = 1
\end{aligned}
\tag{7}
$$

Where:

E_1, E_2 : elasticity modulus of the lamina in the principal directions in the plane of the lamina
G_{12} : shear modulus of the lamina in the plane of the lamina
ν_{12} : Poisson's ratio in the principal directions in the plane of the lamina
ν_R : Poisson's ratio of the resin in the principal directions
ν_F : Poisson's ratio of the fiber in the plane of the fiber in the principal directions
ϕ_{UD} : empirical reduction factor
E_R : elasticity modulus of the resin
E_{F1}, E_{F2} : elasticity modulus of the fiber in the fiber principal directions
G_R : shear modulus of the resin
V_f : fiber volume percentage of the lamina

For the prediction of the elasticity of the composite, the rule of mixtures and the semi-empirical formulas of Halpin and Tsai are available. The basic assumptions for both models are provided by Ghafaar et al.:

- both matrix and fibers are linearly elastic, isotropic, and homogeneous;
- the fibers are perfectly aligned and spaced;
- the matrix is void free;
- the bonding between matrix and fibers is perfect [36]

The CUR 96 utilizes the Halpin-Tsai equations [5]. For a UD-lamina based on E-glas and an unsaturated polyester, CUR 96 provides characteristic values of the above mentioned material properties, based on fiber volume fraction. Equation (7), minus the empirical reduction factor, is also called the rule of mixtures [1]. The rule of mixtures assumes a perfect bonding between fibers and matrix. It illustrates that the elasticity modulus of a lamina will lie between the values of the elasticity moduli of the fibers and the matrix.

For bi-directional laminas:

$$
\begin{aligned}
E_1 &= E_2 = \frac{1}{2} \cdot \left[E_R + (E_{F1} - E_R) \cdot V_f + E_R \cdot \frac{1 + \xi_1 \eta_1 V_f}{1 - \eta_1 V_f} \right] \cdot \phi_{0/90} \\
G_{12} &= \left[\frac{1 + \xi_G \eta_G V_f}{1 - \eta_G V_f} \cdot G_R \right] \cdot \phi_{0/90} \\
\nu_{12} &= \left\{ \nu_R - (\nu_R - \nu_F) \cdot V_f \right\} \cdot \frac{1}{2} \cdot \left[1 + E_R \cdot \frac{\frac{1+\xi_1 \eta_1 V_f}{1-\eta_1 V_f}}{E_R + (E_{F1} - E_R) \cdot V_f} \right] \cdot \phi_{0/90} \qquad (8) \\
\eta_1 &= \frac{\frac{E_{F1}}{E_R} - 1}{\frac{E_{F1}}{E_R} + \xi_1}; \xi_2 = 2 \\
\eta_G &= \frac{\frac{G_F}{G_R} - 1}{\frac{G_F}{G_R} + \xi_G}; \xi_2 = 1
\end{aligned}
$$

These formulas are based on the semi-empirical equations of Halpin and Tsai, where the additional reduction factor $\phi_{0/90} = 0.93$ is applied to cope with material imperfections. For a bidirectional lamina based on E-glass and polyester resin, CUR 96 provides characteristic values of the above mentioned material properties, based on fiber volume fraction.

Thermal expansion coefficient:

$$\begin{aligned}\alpha_1 &= \frac{V_F\alpha_{F1}E_{F1}+V_R\alpha_R E_R}{E_1}\\ \alpha_2=\alpha_3 &= \alpha_{f2}\cdot\sqrt{V_F}+\left(1-\sqrt{V_F}\right)\cdot\left(1+V_F\nu_R E_{F1}/E_1\right)\cdot\alpha_R\end{aligned} \tag{9}$$

Swell expansion coefficient:

$$\begin{aligned}\beta_1 &= (V_F\beta_{F1}E_{F1}+V_R\beta_R E_R)\cdot\frac{1}{E_1}\\ \beta_2=\beta_3 &= \beta_{F2}\sqrt{V_F}+\left(1-\sqrt{V_F}\right)\cdot\left(1+V_F\nu_R E_{F1}/E_1\right)\cdot\beta_R\end{aligned} \tag{10}$$

8.3.5 Laminate properties

A laminate consists of stacked laminas. The CUR 96 states that laminate properties can be determined in three ways [5]. The first way is by the classical laminate theory, which if elaborated in Section 8.3.6. When using this method, *characteristic* values recommended by the CUR 96 should be used. The other method states that values may be derived from test results of comparable composites. If the fiber volume differs, the values should be adjusted adequately as stated by the CUR 96. Last, the composite itself may be tested based on presented tests in the CUR 96. The total fiber content ratio has to be at least 15 %, otherwise strength properties need to be determined with lab experiments.

For the laminate buildup, it is recommended to constructed a symmetric and balanced composite. This is recommended because non-symmetrical laminates may lead to deformations during loading and production.

The strength of a laminate, two strain limits are considered: a linear strain limit of 1.2 % and a shear strain limit of 1.6 % under respectively a uni-axial tension state and pure shear. These limits may be used if, in every principal direction (0°,90°,45°,–45°) at least 12.5 % of the fiber reinforcement is placed. The CUR 96 calls this the simplified strain criterion [5].

For the interlaminar shear strength (ILSS), the CUR 96 gives the following values:

Resin	Interlaminar shear strength MPa
Polyester	20
Vinylester	25
Epoxy	30

Table 10: Interlaminar shear strength of resins, provided by the CUR 96 [5]

8.3.6 Classical laminate theory

This section elaborates the classical laminate theory as presented in the CUR 96 [5], which is used to determine the mechanical properties of laminates. Section 8.3.3 states the assumptions which on which the classical laminate theory rests. The input parameters which are used by the classical laminate theory are the mechanical properties of individual laminas, the geometry of the laminas (thickness), fiber orientation, and the

sequence of the stacked laminas. Methods for determining these mechanical properties ($E_1, E_2, G_{12}, and \nu_{12}$) are presented in the preceding section (Section 8.3.4). There are various software programs available which uses Classical laminate theory to calculate the responses of a composite under a load. Examples are Kolibri and ELamx[2][37, 38].
Hook's law links the stress and strain in a material. This is done by a constant parameter, the elasticity modulus. For an anisotropic material, Hook's law can be formulated in a general form:

$$\sigma_{ij} = E_{ijkl} \cdot \varepsilon_{kl} \tag{11}$$

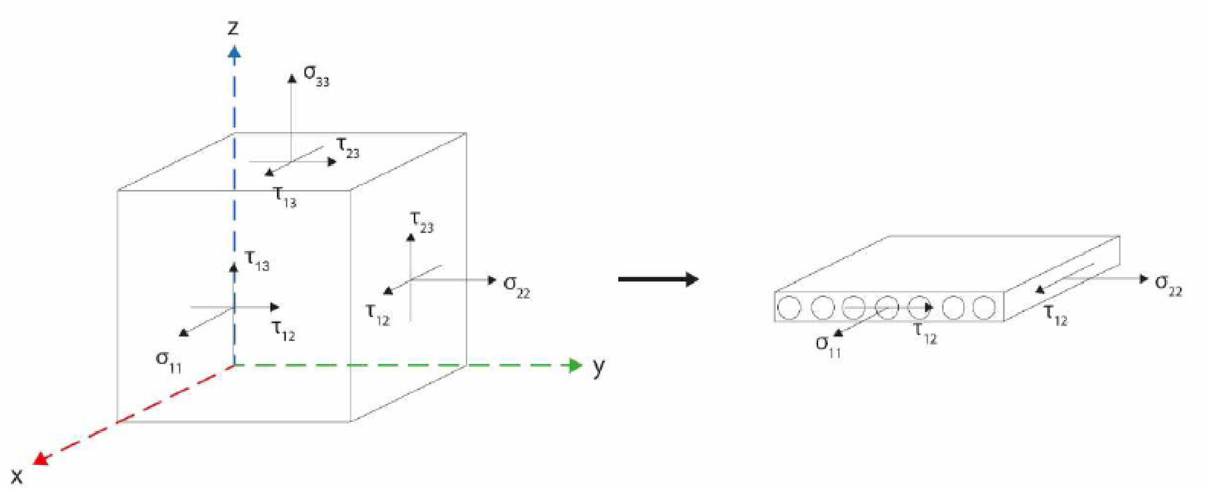

Figure 28: The 9 stress components in the defined axis orientation

Figure 28 illustrates these stress components in the defined axis orientation. Each stress component is governed by 9 strain components, which yields 81 elasticity constants. However, for an orthotropic material has different material properties in two or three orthogonal directions. The elasticity tensor can then be described for a three-dimensional stress state as:

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & 0 & 0 & 0 \\ Q_{21} & Q_{22} & Q_{23} & 0 & 0 & 0 \\ Q_{31} & Q_{32} & Q_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & Q_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & Q_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} \tag{12}$$

Where:

Q_{ijkl} are the stiffness factors

Due to the geometry of the lamina, the stress state can be regarded as two-dimensional. This is because dimensions of length and with are far greater than the thickness of the lamina. For a two-dimensional stress state (also called plane stress), the elasticity tensor

Q can be reduced to:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} \tag{13a}$$

The inverse of this relation is the compliance tensor S relation:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{21} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \tag{13b}$$

Where:

S_{ijkl} are the compliance factors

The elasticity factors can be expressed in terms of the compliance factors:

$$\begin{aligned} Q_{11} &= \frac{S_{22}}{S_{11}S_{22} - S_{12}^2} = \frac{E_1}{1 - \nu_{12}\nu_{21}} \\ Q_{22} &= \frac{S_{11}}{S_{11}S_{22} - S_{12}^2} = \frac{E_1}{1 - \nu_{12}\nu_{21}} \\ Q_{12} &= \frac{S_{22}}{S_{11}S_{22} - S_{12}^2} = \frac{\nu_{21}E_1}{1 - \nu_{12}\nu_{21}} = \frac{\nu_{12}E_2}{1 - \nu_{12}\nu_{21}} \\ Q_{66} &= \frac{1}{S_{66}} = G_{12} \end{aligned} \tag{14}$$

Where:

$$\nu_{12}E_2 = \nu_{21}E_1 \Rightarrow \frac{\nu_{12}}{E1} = \frac{\nu_{21}}{E_2} \Rightarrow \frac{\nu_{12}}{\nu_{21}} = \frac{E_1}{E_2}$$

The indices of the elasticity moduli coincide with the principal directions (1 being longitudinal to the fiber direction and 2 being lateral to the fiber direction, for a UD-lamina). Then the compliance factors can be expressed as:

$$\begin{aligned} S_{11} &= \frac{1}{E_1} \\ S_{22} &= \frac{1}{E_2} \\ S_{12} &= -\frac{\nu_{xy}}{E_1} = -\frac{\nu_{yx}}{E_2} \\ S_{66} &= \frac{1}{G_{12}} \end{aligned} \tag{15}$$

In a well designed laminate, not all the laminas are orientated in the same direction. Instead, they are orientated, in general, in the 0°,90°,45°,−45° directions. This degree is called the orientation angle ϕ. For different orientation angles the mechanical properties

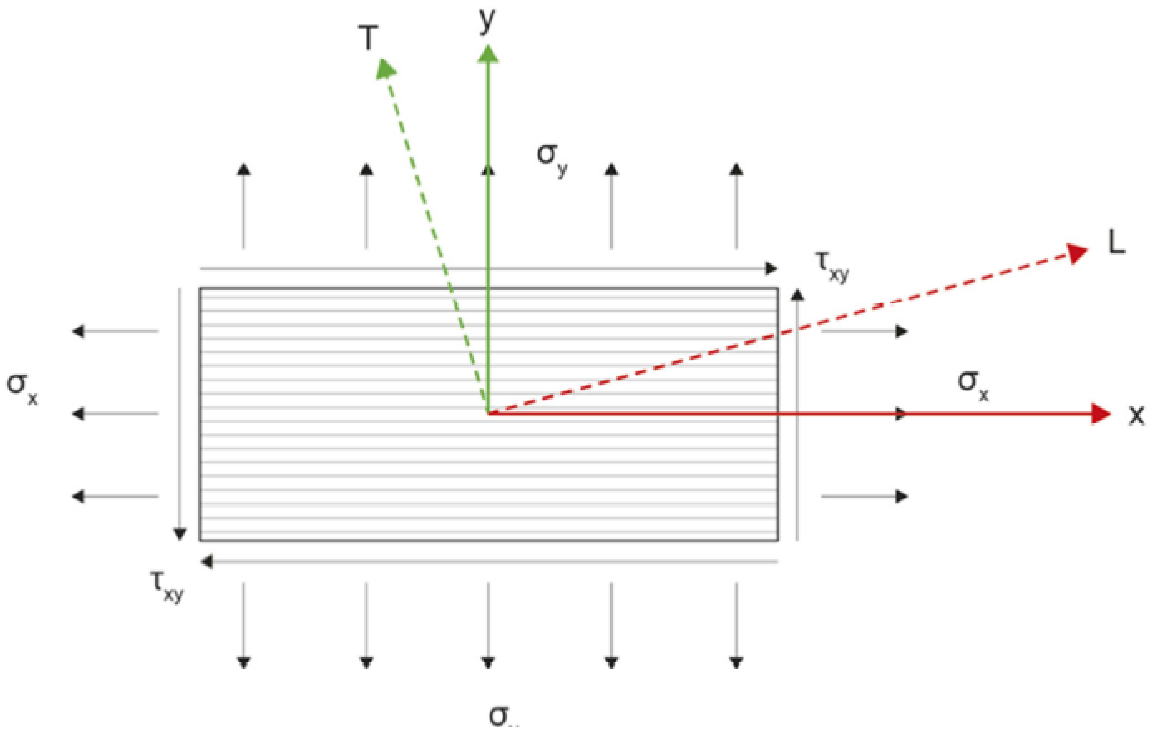

Figure 29: The stress transformation due to a rotation in the plane of the lamina

vary in the principal directions of the laminate. Therefore, they need to be transformed. Figure 29 illustrates the axis orientation if the material properties of a lamina needs to determined in a random direction (L and T) with respect to the fiber orientation (x and y for respectively the longitudinal direction the transverse direction).
The relation between the material properties in different directions is denoted by the transformation matrix T:

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{TL} \end{Bmatrix} = T \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} \tag{16}$$

$$\begin{Bmatrix} \varepsilon_L \\ \varepsilon_T \\ \varepsilon_{TL} \end{Bmatrix} = T \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{Bmatrix} \tag{17}$$

The transformation matrix T and its inverse T^{-1} are described by:

$$T = \begin{bmatrix} c^2 & s^2 & 2sc \\ s^2 & c^2 & -2sc \\ -sc & sc & c^2 - s^2 \end{bmatrix} \tag{18a}$$

$$T^{-1} = \begin{bmatrix} c^2 & s^2 & -2sc \\ s^2 & c^2 & 2sc \\ sc & -sc & c^2 - s^2 \end{bmatrix} \tag{18b}$$

With the transformation matrix and its inverse defined, the following relation can be made:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{Bmatrix} = T^{-1}QT \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \frac{1}{2}\gamma_{12} \end{Bmatrix} \tag{19a}$$

or:

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \end{Bmatrix} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \frac{1}{2}\gamma_{12} \end{Bmatrix} \tag{19b}$$

The $\overline{Q}$ components are:

$$\begin{aligned} \overline{Q}_{11} &= Q_{11}c^4 + Q_{22}s^4 + 2\left(Q_{12} + 2Q_{66}\right)s^2c^2 \\ \overline{Q}_{22} &= Q_{11}s^4 + Q_{22}c^4 + 2\left(Q_{12} + 2Q_{66}\right)s^2c^2 \\ \overline{Q}_{12} &= \left(Q_{11} + Q_{22} - 4Q_{66}\right)s^2c^2 + Q_{12}\left(c^4 + s^4\right) \\ \overline{Q}_{66} &= \left(Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66}\right)s^2c^2 + Q_{66}\left(c^4 + s^4\right) \\ \overline{Q}_{16} &= \left(Q_{11} - Q_{12} - 2Q_{66}\right)sc^3 - \left(Q_{22} - Q_{12} - 2Q_{66}\right)cs^3 \\ \overline{Q}_{26} &= \left(Q_{11} - Q_{12} - 2Q_{66}\right)s^3c - \left(Q_{22} - Q_{12} - 2Q_{66}\right)c^3s \end{aligned} \tag{20a}$$

The inverse of the $\overline{Q}$ matrix is the stiffness matrix $\overline{S}$ with the elements:

$$\begin{aligned} \overline{S}_{11} &= S_{11}c^4 + S_{22}s^4 + \left(2S_{12} + S_{66}\right)s^2c^2 \\ \overline{S}_{22} &= S_{11}s^4 + S_{22}c^4 + \left(2S_{12} + S_{66}\right)s^2c^2 \\ \overline{S}_{12} &= \left(S_{11} + S_{22} - S_{66}\right)s^2c^2 + S_{12}\left(c^4 + s^4\right) \\ \overline{S}_{66} &= 2\left(2S_{11} + 2S_{22} - 4S_{12} - S_{66}\right)s^2c^2 + S_{66}\left(c^4 + s^4\right) \\ \overline{S}_{16} &= 2\left(2S_{11} - 2S_{12} - S_{66}\right)sc^3 - 2\left(2S_{22} - 2S_{12} - S_{66}\right)cs^3 \\ \overline{S}_{26} &= 2\left(2S_{11} - 2S_{12} - S_{66}\right)s^3c - 2\left(2S_{22} - 2S_{12} - S_{66}\right)c^3s \end{aligned} \tag{20b}$$

With these formulas, a relationship between the stresses and strains for a random orientation angle is established. For the determination of the response of a laminate to a load, the way of stacking, the thickness and the size of the load need to be described.
When a laminate bends, the cross section tends to shear. However, in classical laminate theory, it is assumed that the cross section remains straight (Euler-Bernoulli hypothesis) and that shear deformations are negligible. Also, it is assumed that no slip occurs between the laminas. Figure 30 shows the local axis system and the bending parameters u_0, v_0, w_0 in the $x, y,$ and$z$ directions at B.
The deflection of C is given by:

$$\begin{aligned} u &= u_0 - z\alpha \\ \alpha &= \frac{\partial w_0}{\partial x} \\ u &= u_0 - z\frac{\partial w_0}{\partial x} \end{aligned} \tag{21}$$

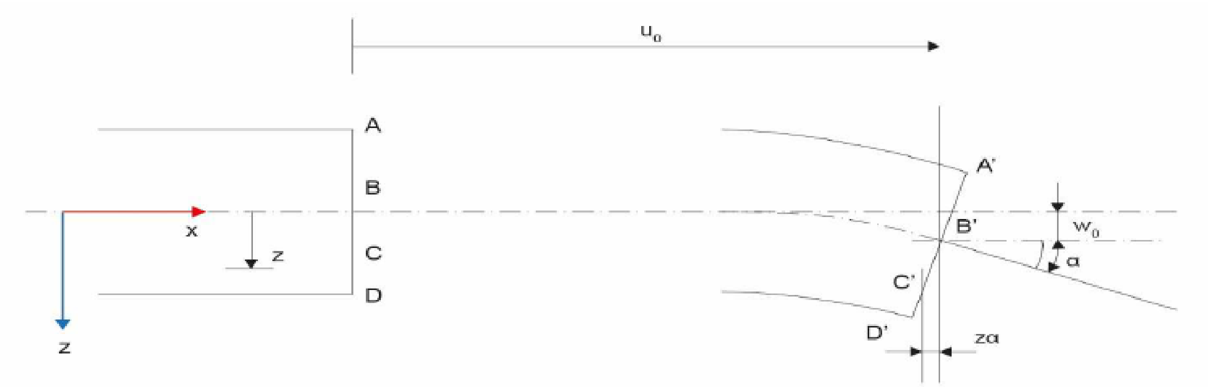

Figure 30: Bending of a laminate and the local defined axis

Also, the following relation can be derived:

$$v = v_0 - z\frac{\partial w_0}{\partial y} \tag{22}$$

The strain ε_z can be neglected because it is assumed that the strain in the plane of ABCD is significantly smaller than the displacement w_0 of the cross section. With Equation (21) and Equation (22) the following relations can be derived:

$$\begin{aligned} \varepsilon_x &= \frac{\partial u}{\partial x} = \frac{\partial u_0}{\partial x} - z\frac{\partial^2 w_0}{\partial x^2} \\ \varepsilon_y &= \frac{\partial v}{\partial y} = \frac{\partial v_0}{\partial y} - z\frac{\partial^2 w_0}{\partial y^2} \\ \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \frac{\partial u_0}{\partial y} - \frac{\partial v_0}{\partial x} - 2z\frac{\partial^2 w_0}{\partial x \partial y} \end{aligned} \tag{23}$$

The formulas of Equation (23) can be defined with respect to the neutral axis:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_u \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_u^0 \\ \gamma_{xy}^0 \end{bmatrix} + z \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix} \tag{24}$$

Where:

$$\varepsilon_x^0 = \frac{\partial u_0}{\partial x}$$
$$\varepsilon_y^0 = \frac{\partial v_0}{\partial y}$$
$$\gamma_{xy}^0 = \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x}$$
$$k_x = -\frac{\partial^2 w_0}{\partial x^2}$$
$$k_y = -\frac{\partial^2 w_0}{\partial y^2}$$
$$k_{xy} = -2\frac{\partial^2 w_0}{\partial x \partial y}$$
$$z = \text{distance from the neutral axis to the fiber}$$

Combining Equation (24) Equation (19) we get the relation with which we can calculate the stress state of a lamina:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} \tag{25}$$

While strains in general vary linear over the thickness of the laminate, stresses will not. This is due to the different material properties in a certain direction which change due to a rotation of the lamina with respect to the fiber direction. Therefore, it is more convenient to work with forces on the laminate. Figure 31 illustrates the forces acting on a laminate for a plane stress mode.

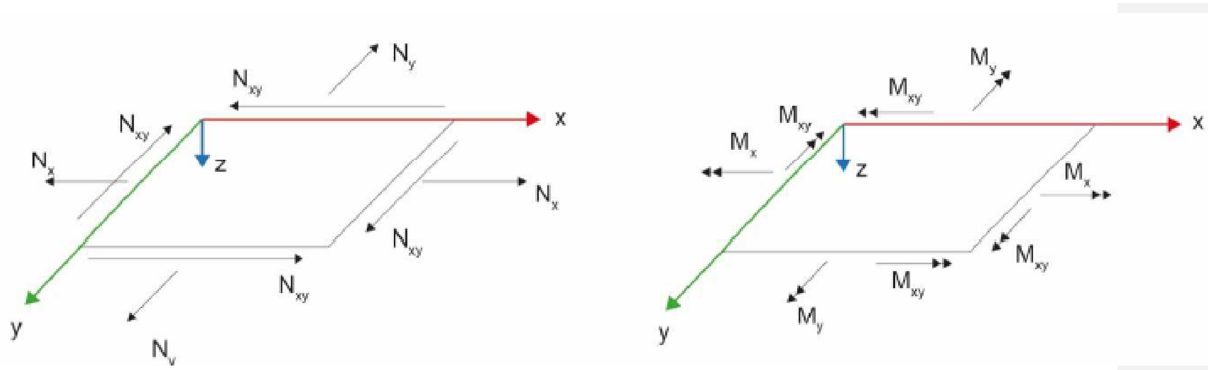

Figure 31: Definition of forces in a laminate

These forces are:

$$\begin{aligned} N_x &= \int_{-h/2}^{h/2} \sigma_x dz \quad & M_x = \int_{-h/2}^{h/2} \sigma_x z dz \\ N_y &= \int_{-h/2}^{h/2} \sigma_y dz \quad & M_x = \int_{-h/2}^{h/2} \sigma_y z dz \\ N_{xy} &= \int_{-h/2}^{h/2} \tau_{xy} dz \quad & M_{xy} = \int_{-h/2}^{h/2} \tau_{xy} z dz \end{aligned} \tag{26}$$

Now, consider the following schematic cross section of a laminate:

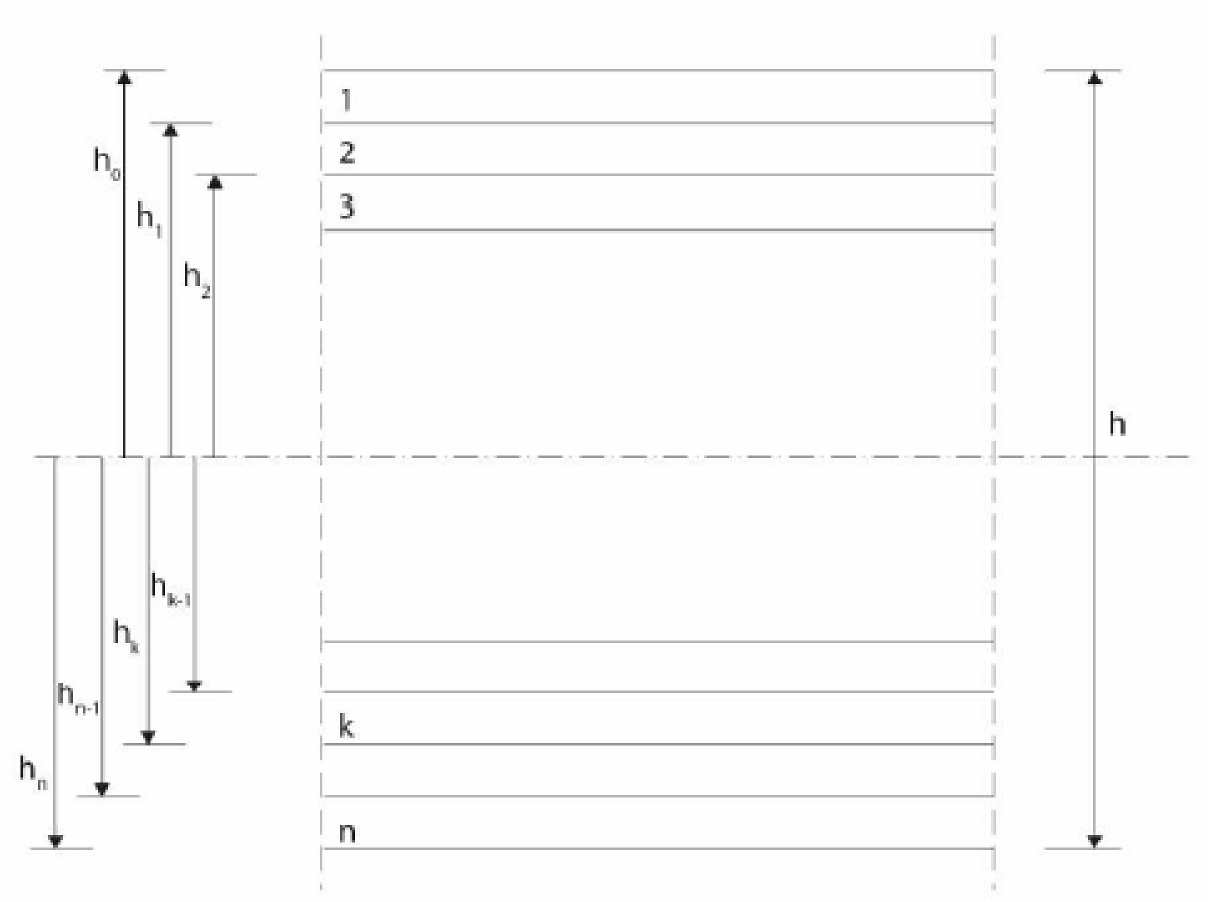

Figure 32: Schematic cross section of a laminate and its n laminas

If the tension in a lamina is regard constant, the relation between the forces on the laminate and the stresses in the laminas is:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k dz \tag{27a}$$

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k zdz \tag{27b}$$

Combining above relations with Equation (25) we get:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix}_k = \sum_{k=1}^{n} \left\{ \int_{h_{k-1}}^{h_k} \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} dz + \int_{h_{k-1}}^{h_k} \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} zdz \right\} \tag{28a}$$

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix}_k = \sum_{k=1}^{n} \left\{ \int_{h_{k-1}}^{h_k} \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} zdz + \int_{h_{k-1}}^{h_k} \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix}_k \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} z^2dz \right\} \tag{28b}$$

If we assume that the strains on the neutral line of a lamina and the curvature of the panel are constant for every lamina in the laminate, the equations above can be simplified:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix}_k = \begin{bmatrix} \overline{A}_{11} & \overline{A}_{12} & \overline{A}_{16} \\ \overline{A}_{12} & \overline{A}_{22} & \overline{A}_{26} \\ \overline{A}_{16} & \overline{A}_{26} & \overline{A}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + \begin{bmatrix} \overline{B}_{11} & \overline{B}_{12} & \overline{B}_{16} \\ \overline{B}_{12} & \overline{B}_{22} & \overline{B}_{26} \\ \overline{B}_{16} & \overline{B}_{26} & \overline{B}_{66} \end{bmatrix} \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} \tag{29a}$$

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix}_k = \begin{bmatrix} \overline{B}_{11} & \overline{B}_{12} & \overline{B}_{16} \\ \overline{B}_{12} & \overline{B}_{22} & \overline{B}_{26} \\ \overline{B}_{16} & \overline{B}_{26} & \overline{B}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + \begin{bmatrix} \overline{D}_{11} & \overline{D}_{12} & \overline{D}_{16} \\ \overline{D}_{12} & \overline{D}_{22} & \overline{D}_{26} \\ \overline{D}_{16} & \overline{D}_{26} & \overline{D}_{66} \end{bmatrix} \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} \tag{29b}$$

Where:

$$\begin{aligned} A_{ij} &= \sum_{k=1}^{n} \left(\overline{Q}_{ij}\right)_k (h_k - h_{k-1}) \\ B_{ij} &= \frac{1}{2} \sum_{k=1}^{n} \left(\overline{Q}_{ij}\right)_k \left(h_k^2 - h_{k-1}^2\right) \\ D_{ij} &= \frac{1}{3} \sum_{k=1}^{n} \left(\overline{Q}_{ij}\right)_k \left(h_k^3 - h_{k-1}^3\right) \end{aligned} \tag{30}$$

In a short notation, the relation between the forces on the laminate and the strain and curvature can be written as:

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon^0 \\ k \end{Bmatrix} \tag{31}$$

Where A is the normal stiffness matrix, B the coupling matrix, and D the bending stiffness matrix.
It should be noted that the coupling matrix is zero when the laminate is mirrored in the neutral axis regarding material properties and dimensions.

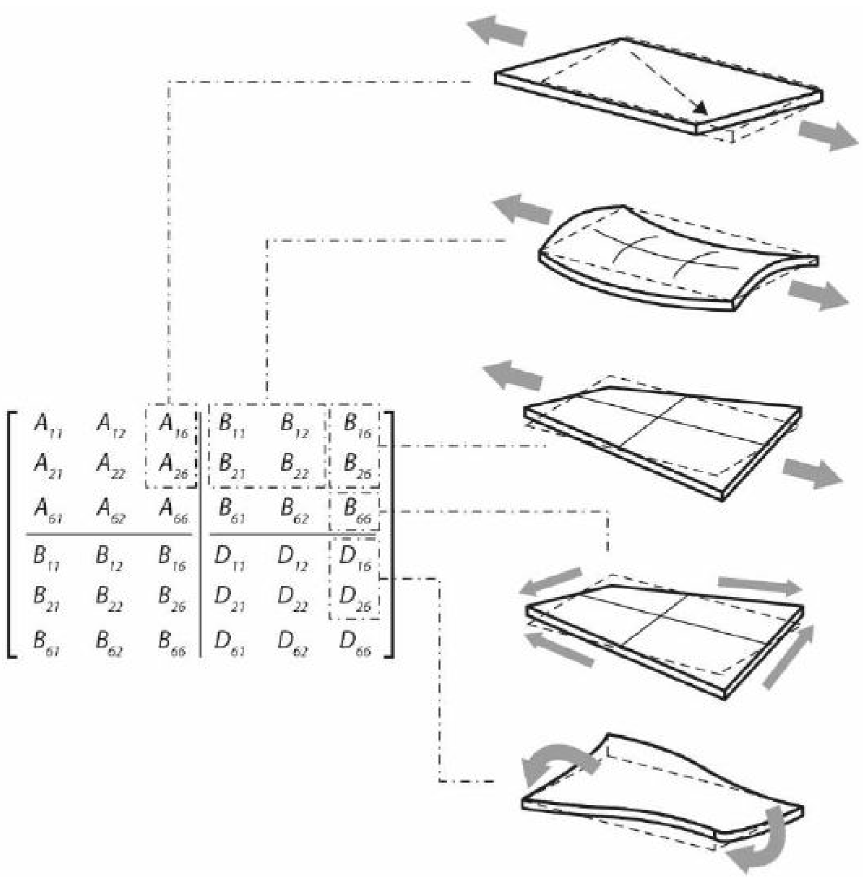

Figure 33: Graphical illustration of effect which some stiffness components have on shape of the composite [5]

8.3.7 ULS: Ultime limit state

In the ULS, the strength and stability of the structure are tested. The CUR 96 states that a test can either take place on either one of the following levels: lamina level, laminate level, and cross sectional level [5]. A lamina, laminate, or cross section is considered to fail if it reaches its failure point. The failure point has an acompanyning failure strain. Before the failure point, the point is reached where the first cracks are formed. This is accompanied by a strain which indicates the start of the crack forming area. Together they make up a bi-linear function in the stress-strain diagram. The CUR 96 indicates when to test at which level.
On a lamina level, the following criterion has to be met:

$$\left(\frac{\sigma_{1,Ed}}{f_{1,Rd}}\right)^2 + \left(\frac{\sigma_{2,Ed}}{f_{2,Rd}}\right)^2 + \left(\frac{\tau_{12,Ed}}{\tau_{12,Rd}}\right)^2 - \frac{\sigma_{1,Ed} \cdot \sigma_{2,Ed}}{f_{1,Rd}^2} \leq 1 \tag{32}$$

Where:

$\sigma_{1,Ed}$: stress in the fiber direction
$\sigma_{2,Ed}$: stress in the transverse direction with respect to the fiber
$\tau_{12,Ed}$: shear stress
$f_{1,Rd}$: design strength in the fiber direction
$f_{2,Rd}$: design strength in the transverse direction with respect to the fiber
$\tau_{12,Rd}$: shear strength

CUR 96 presents how the strength parameters can be determined [5].
On a laminate level, the simplified strain criterion maintained (see Section 8.3.5). For a uni-axial stress state, or pure shear, the following criteria have to be met:

$$\begin{aligned} \varepsilon_{x,Ed} &\leq \frac{\eta_c \cdot 1.2\%}{\gamma_M} \\ \varepsilon_{y,Ed} &\leq \frac{\eta_c \cdot 1.2\%}{\gamma_M} \\ \varepsilon_{xy,Ed} &\leq \frac{\eta_c \cdot 1.6\%}{\gamma_M} \end{aligned} \tag{33}$$

On a cross sectional level, a conservative relation between the design values of the loads and their linear resistance may be used. The following criterion applies:

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{Y,Ed}}{M_{Y_Rd}} + \frac{M_{Z,Ed}}{M_{Z_Rd}} + \frac{V_{Y,Ed}}{V_{Y_Rd}} + \frac{V_{Z,Ed}}{V_{Z_Rd}} + \frac{T_{Ed}}{T_{Rd}} \leq 1 \tag{34}$$

Where the Ed index stand for the design value for the occurring cross sectional forces and the Rd index stands for the design value of the resistance. The determination of these values is elaborated in the CUR 96 [5]

8.3.8 SLS: Serviceability limit state

According to the CUR 96, for the SLS the structure has to comply with the following criteria:

- deformations which change the appearance of the structure, negatively influence the comfort of the people and the functions of the structure
- vibrations which cause discomfort for people or limit the functions of the structure
- damage which works disadvantageous on the appearance of the structure, the durability or the functionality of the structure [5]
  The CUR 96 notes that composites have strength compared to their stiffness. Therefore, SLS criteria may be more governing than ULS criteria. Detailed elaboration of these criteria and how to test them are presented in [5].

8.3.9 Joints

The CUR 96 distinguishes two joint types: glued connections and mechanical connections. Glued joints have to be tested for:

- failure of the laminate
- failure of joint by shear
- failure of the joint by transverse stress on the glue connection

The criterion which has to be met is:

$$\begin{aligned} \frac{\sigma_{3a,Ed}}{f_{3a,Rd}} &\leq 1 \\ f_{3a,Rd} &= \frac{\eta_{PCa} \cdot R_k}{\gamma_{Ma}} \\ \frac{\tau_{13a,Ed}}{\tau_{13a,Rd}} &\leq 1 \\ \tau_{13a,Rd} &= \frac{\eta_{PCa} \cdot R_k}{\gamma_{Ma}} \end{aligned} \tag{35}$$

Where:

R_k is the characteristic strength of the glue connection as determined from a test

For combined stress states, the following criterion has to be met:

$$\left(\frac{\sigma_{3a,Ed}}{f_{3a,Rd}}\right)^2 + \left(\frac{\tau_{13a,Ed}}{\tau_{13a,Rd}}\right)^2 \leq 1 \tag{36}$$

8.3.10 Laminate design recommendation

Several design recommendation are given based on theory and practical experience

The most frequent cited design recommendation is the recommendation to build a symmetrical (distance to mid-plane, thickness, material, and fiber orientation) laminate with respect to the middle plane of the composite [1, 13, 23]. This eliminates the extension-bending coupling. This effect is undesirable because it reduces the effective stiffness of the laminate. Mallick also states that the bending-twist coupling can be removed by designing the laminate in such way so that the stiffness componentsD_{16}andD_{26} equal to zero by only using 0,90 or 0 and 90 fiber orientation angles. However, the effect of the bending-twist coupling on the elasticity is far smaller than extension-bending coupling.

Nijhof recommends to limit the same orientation angle between laminas. As the mechanical properties and thermal properties change with respect to a defined direction if the angle orientation changes, bigger angles induce bigger differences between the laminas [23]. Nijssen states that stiffness jumps between laminas should be avoided. This can be done by limiting the mutual fiber angels to for instance a difference of 60°.

Nijssen also recommends to work with balanced laminates. For each lamina with the fiber orientation of $+\theta$, a lamina of $-\theta$ should be placed [13]. Mallick states that is better to alternate fiber orientation angles instead of stacking orientation angles on each other while balancing the laminate[1]. For instance, $\left[+\theta/-\theta/+\theta/-\theta/\right]_S$ and not $\left[+\theta/+\theta/-\theta/-\theta/\right]_S$. However, Mallick also states that when 0, 90, and $\pm\theta$ directions, then adjacent $+\theta$ and $-\theta$ should be avoided. Nijhof recommends to not stack too many laminas of the same fiber orientation. Because if interlaminar stresses occur, a thicker lamina will result in larger interlaminar stresses because the generated forced are larger while the interlaminar plane remains the same [23].

By designing an orthotropic laminate, the behavior of the laminate is more insightfull [23]. If a laminate is orthotropic, then $A_{16} = A_{26} = 0$. Nijssen notes that this can make the laminate relatively heavy [13].

9 Joints

Joints are important components in structures which come with design challenges. At the location of a joint, the continuity in load transfer interrupted and stress concentrations occur [2].
In general, FRP joints can be categorized in two types: adhesive joints and mechanical joints. This section further elaborates these two types of joints because of their common use and the availability of guidelines provided by the CUR96 [5].

Adhesive joints are joints where two or multiple elements are joint trough a bonding substance; mechanical joints connects elements by means of bolts or rivets [1]. Both joint types possess different advantages with respect to the other [2, 1, 3]:

- For adhesive joints, the stress concentration is lower since the load transfer is through a surface rather than a single point. This is an important advantage because FRP has limited ductile behavior which makes it less resistant to such stress concentrations.
- Due to the uniform stress distribution, adhesive joints have more resistance against flexural, fatigue, and vibration stresses compared to mechanical joints
- The weight-contribution of adhesive joints to the structure is negligible compared to mechanical joints
- Adhesive joints seal the joint, making it less vulnerable to corrosion and moisture
- Mechanical joints are easier to inspect than adhesive joints
- When parts are replaced or removed, the laminate is not affected since the mechanical joint (e.g. bolt) can be removed; when separating adhesive joints, damage to the laminate will occur
- Mechanical joint are better suited for load transmission perpendicular to the laminate area, whereas adhesive joints are stronger parallel to the laminate area
- Adhesive bonding is often less expensive compared to mechanical bonding
- In contrast to mechanical joints, adhesive joints often require a surface treatment of the laminate which heavily influences the quality of the joint

Most often, the ULS criteria govern the design of the joints and not the SLS criteria [5].

9.1 Adhesive joints

9.1.1 Types of adhesive joints

Figure 34 illustrates some common types of adhesive joints. In single lap joints, an eccentricity is found and the joint may rotate if forces become large; this can be avoided by utilizing double lap joints. By reducing gradually reducing the thickness at the end of the laminas, the peak stresses can be reduced in the adhesive component and the lamina [5].

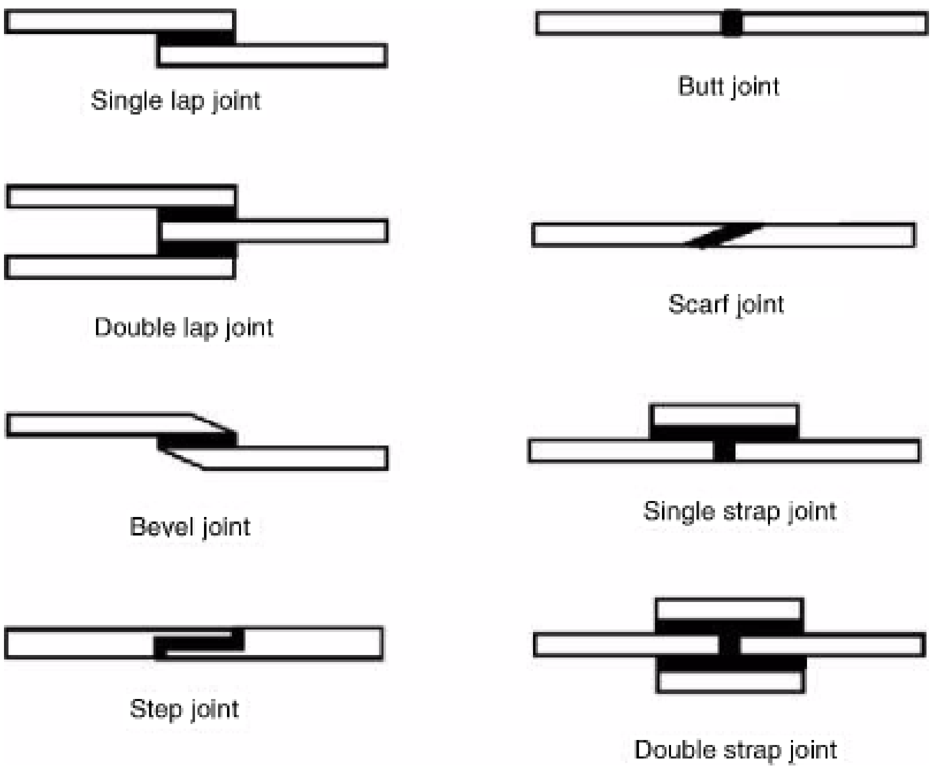

Figure 34: Overview of different adhesive joints[2]

9.1.2 Failure of adhesive joints

Figure 35 illustrates some common failure types of bonds [15]. Adhesive failure is when the adhesive component (i.e. the bond) fails to attach to the laminate. Cohesive failure occurs of the internal strength of the bond is insufficient. A combination of these two may occur as well. Also, the laminate itself can fail, which is called substrate failure [15].

9.1.3 Design criteria for adhesive joints

The CUR96 recommends to test adhesive joints on the following criteria [5]:

- failure of the laminate
- failure of the bond due to shear stress
- failure of the bond due to peel stress

The failure of the laminate is treated in Section 8. The other two, failure of the bond due to shear stress and peel stress are briefly treated in the remainder of the section.

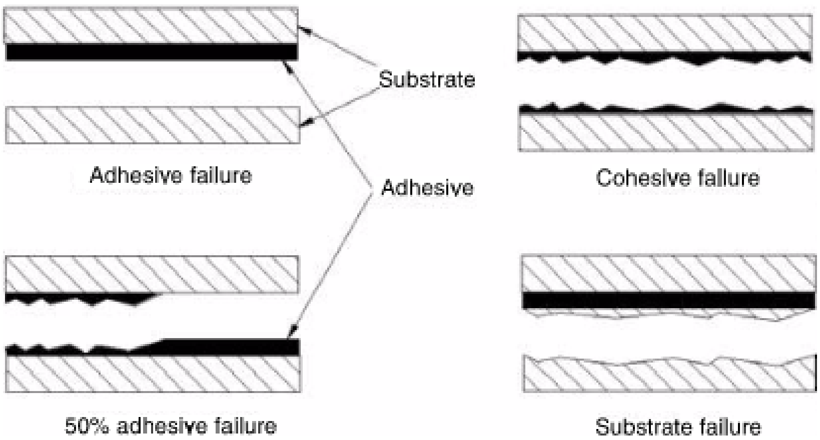

Figure 35: Types of failure modes of bonds [2]

Strength on shear stress
The check on strength for the shear stress is given as [5]:

$$\frac{\tau_{13a,Ed}}{\tau_{13a,Rd}} \leq 1$$
$$\tau_{13a,Rd} = \frac{\eta_{ca} * R_k}{\gamma_{Ma}}$$

Where R_k is the characteristic strength of the adhesive binder.

Strength on peel stress
The peel stress is the stress normal to the area of the laminate. The check on strength for the peel stress is given as [5]:

$$\frac{\sigma_{13a,Ed}}{f_{13a,Rd}} \leq 1$$
$$f_{13a,Rd} = \frac{\eta_{ca} * R_k}{\gamma_{Ma}}$$

Combination of shear and peel stress
When both shear stresses and peel stresses occur, they have to be checked in combination:

$$\left(\frac{\sigma_{13a,Ed}}{f_{13a,Rd}}\right)^2 + \left(\frac{\tau_{13a,Ed}}{\tau_{13a,Rd}}\right)^2 \leq 1$$

9.2 Mechanical joints

Mechanical joints connect materials by bolts, screws, or rivets as depicted in Figure 36.

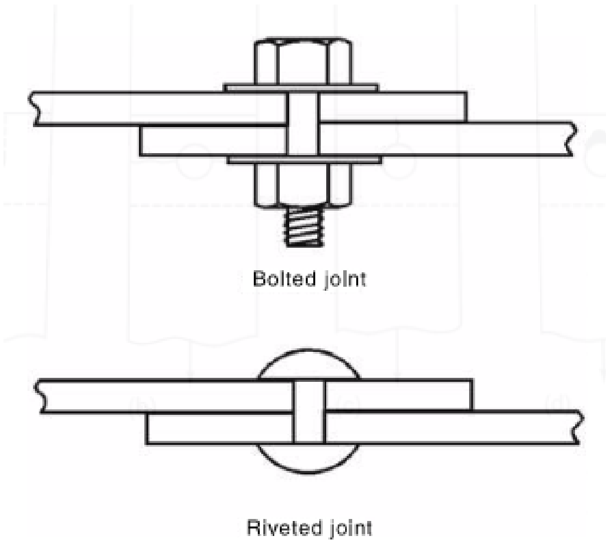

Figure 36: Mechanical joint with a bolt and a rivet [2]

9.2.1 Failure of mechanical joints

Figure 37 illustrates some basic failure modes for mechanical joints, which involves failure of the laminate: shear failure, net-tensile failure, cleavage and bearing failure. The bolt itself can fail as well. BIJL products utilizes stainless steel bolts since FRP bolts exhibit too much creep [39].

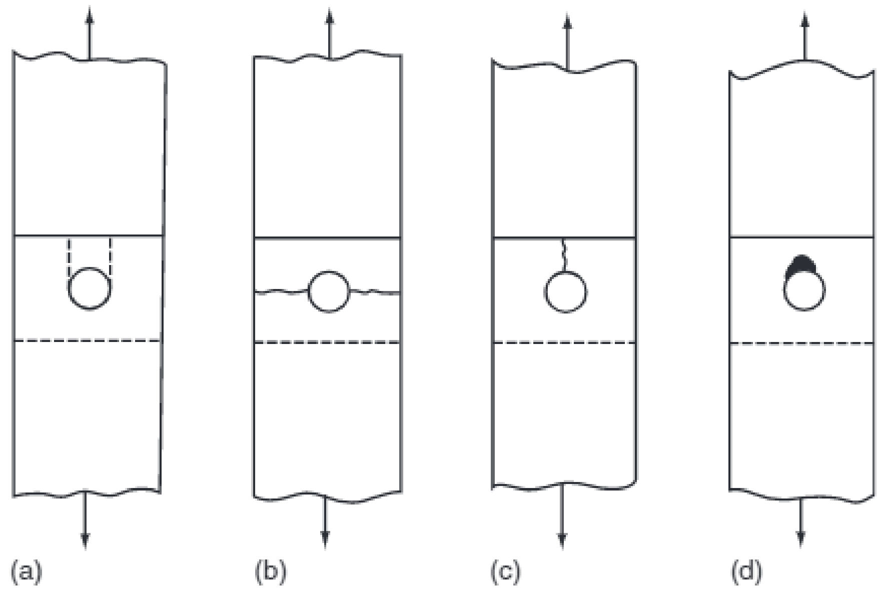

Figure 37: Basic failure modes for mechanical joints [1]: (a) shear failure, (b) net-tensile failure, (c) cleavage, (d) bearing failure

9.2.2 Types of mechanical joints

Figure 38 illustrates common mechanical joint types [2].

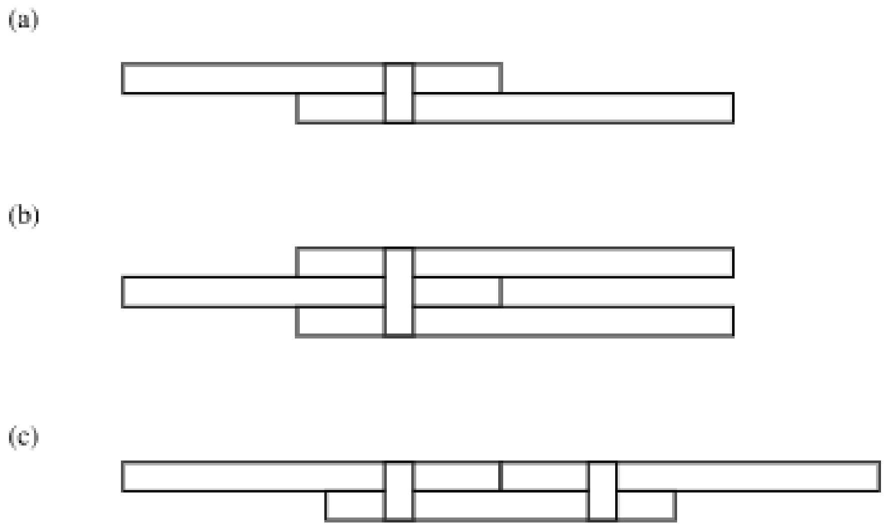

Figure 38: Different types of mechanical joints: (a) single lap, (b) double lap, (c) butt [2]

9.2.3 Design criteria for adhesive joints

The CUR96 recommends to test joints related to their different failure modes, as presented in Section 9.2.1 [5]:

- Failure of the bolt
- Failure of the laminate
  - In-plane failure modes:
    - Bearing failure
    - Net-tensile failure
    - Shear failure
    - Cleavage
    - Bckling of the laminate at the pressure site of the bolt hole
  - Out-of-plane failure modes:
    - Shear puncture
    - Interlaminar shear

10 Durability

The most evident advantage of exploring the usage of FRP composites in marine structures are its durable properties. Good durable properties enhances the life time of the structure. Also, maintenance costs could be lower. Together, these may results in lower life cycle costs and lower environmental impact of the hydraulic structure.
The CUR 96 recommends, regarding the durability aspects of the construction, that the following effect need to be incorporated in the design:

- The chemical and physical environment:
  - UV light
  - Temperature influences
  - Moister, water and chemicals
- Time-dependent effects:
  - Creep
  - Stress relaxation
  - Wearing and deterioration
- Fatigue
- Extraordinary loads and load cases:
  - Impact loads
  - Lightning strike, electric charges
  - Combinations of (impact)damage and fatigue
  - Fire
  - Vandalism
- Inspection and maintenance [5]

The occurrence of these aspects need to be set as boundary conditions in the design of the FRP jetty. As individual influences may be severe, a combination of influences may lead to bigger impact than their sum.

The CUR 96 consideres several characteristics of laminates which determine the durability of an FRP composite [5]. First, the amount of trapped air, or void content, influences the durability. Second, the quality of the hardening process of the resin. Third, the chemical resistance of the used materials in the composite. And last, the characteristics of the interface between the fibers and the resin.
Pigments and fillers can greatly enhance the durability of FRP composite. However, an excess of these pigments and fillers might have a negative influence on the durability of the FRP composite [5].

10.1 Influences of moisture on composites

The influence of water and moister may negatively influence the mechanical- and physical properties of the composite. Mallick states that the presence of water negatively influences the tensile strength of glass fibers [1].
Besides influencing the mechanical- and physical properties, water absorption may also cause damage. Nijssen states that most resins can absorb water, which will increase the weight of the structure [13]. This process is reversible: water absorbed by the resin may be released again. However, if damage is induced, this may be irreversible. The damage is done because the accumulated water disrupts the bonding between the polymer chains. Also, the water can freeze and its expansion induces stresses which may lead to the failure

of the composite. Nijssen states that particularly polyester resins are sensitive to damage due to water absorption. Resins which are have a better moisture resistance are vinylester and epoxy esters. Also, a protective outer layer in the form of a gel coat may be applied to enhance moisture resistance. An important note that Nijssen makes is that "almost all thermoplastics are insensitive to moisture, except for polyamide (nylon)" [13].
In a research on the effect of water ageing on the mechanical properties of flax and glass fiber composites, Apolinario et al. [40] found that the tensile modulus of glass-fiber reinforced composites was only slightly affected.
Chandra Ray and Rathore reviewed literature regarding the environmental damage and degradation of FRP composites [41]. They found a research by Lassila et al. where the flexural strength of E-glass fibers was tested. In the research, specimens with a 45 % volume fraction were tested in dry conditions and in wet conditions. For the wet conditions, the specimens were submerged into water for 30 days. For the dry specimens, a flexural strength of 759 MPa to 916 MPa was found, for the wet specimens a flexural strength of 420 MPa to 607 MPa was found.

10.2 Lifetime expectancy

As the jetty is being exposed to external conditions, the material will deteriorate. This will in turn reduces the mechanical- and physical properties of the composite.

The CUR 96 states that field tests and accelerated aging tests indicated that FRP composites can easily reach a life span of 50 years under Dutch climate influences [5]. At the end of 2016, FiberCore Europe is placing a bio-based FRP bridge which is expected to last of 100 years [18], see also Section 13.1.

Helbling et al. made several recommendations in order to the durability, or life expectancy, of an FRP structure. They noted that "careful selection of materials, quality control during processing, and use of appropriate coatings can result in FRP materials and components that show significantly enhanced durability over conventional materials under these exposure conditions" [42]. The remainder of this subsection highlights some of these recommendations.
Whilst both fibers and the polymer matrix are susceptible for wear and deterioration, the resin plays a very important role in protecting the fiber. Therefore, an appropriate epoxy or vinylesther resin should be selected if the durability of the structure needs to be increased.
A protection layer around the FRP component should be applied in order to prevent rapid moisture and chemical intrusion into the composite, reaching the fibers. So, the resin layer at the surface of the FRP component should be thick enough to provide a buffer zone. With the use of gel coats and surface scrim layers, this effect may be further reduced.
FRP parts should be fully cured before installing them in marine environments. If a part is not fully cured, the moisture susceptibility of the resin increases.

10.3 Failure mechanisms for FRP composites

Failure mechanism in FRP composite are complex. This is largely due to the orthotropic properties of laminates. Most failure mechanisms are the result of failure of the fiber or shear and tension failure of the matrix [41]. Due to the combination of influences which generate the possible failure modes, in research often several failure modes have to be described when laboratory testing failure modes. This subsection first highlights the strength and strain limits of laminas. Then, failure mechanisms are described.

10.3.1 Failure prediction criteria

Materials fail under a certain stress state and the accompanying strain state. Failure criteria are set up to give boundaries when materials fail under certain critical stress/strain states. The envelope of these critical states are indicated by failure criteria [23]. They should be reliable and easy to test in order to make them efficient in engineering applications. Several criteria which are relevant for FRP engineering are considered in this section. These criteria are based on orthotropic materials. For the failure of FRP composites it may be assumed that this results from micro defects in the composite [23].

The *Maximum stress criterion* assumes that each of the stress components has a an upper limit and lower limit, being independent from each other [23]. This can be formulated as following [1]:

$$
\begin{aligned}
-S_{Lc} \leq &\sigma_{11} \leq S_{Lt} \\
-S_{Lc} \leq &\sigma_{22} \leq S_{Lt} \\
-S_{Lc} \leq &\tau_{12} \leq S_{Lt}
\end{aligned}
$$

Where:

S_{Lt} : longitudinal tensile strength
S_{Tt} : transverse tensile strength
S_{Lc} : longitudinal compressive strength
S_{Tc} : transverse compressive strength
S_{LTs} : in-plane shear strength

The *Maximum deformation criterion* or *Maximum Strain Theory* assumes that, instead of a stress, a lamina fails when a strain limit is reached [1]. This can be expressed in the following relations:

$$
\begin{aligned}
-\varepsilon_{Lc} \leq &\varepsilon_{11} \leq \varepsilon_{Lt} \\
-\varepsilon_{Tc} \leq &\varepsilon_{22} \leq \varepsilon_{Tt} \\
-\gamma_{LTs} \leq &\gamma_{12} \leq \gamma_{LTs}
\end{aligned}
$$

10.3.2 Failure mechanisms

When a lamina fails the overal stiffness of a laminate decreases which leads to larger stresses and strains in the other laminas. However, this does not mean that the laminate fails [1]. Mallick captures several models which deal with the failure of a lamina in a laminate. These are the total discount method, the limited discount method, and the residual property method. In the total discount method, no stiffness and strength properties are given to the failed lamina. For the limited discount method, several material properties are set to zero. If the lamina the matrix of the lamina has failed, then the transverse and shear modes are set to zero. If the fiber fails in the lamina, then the total discount method is adopted. The residual property method, the stiffness and strength capabilities are not completely discarded but a residual capacity is assigned to the failed lamina.

11 Environmental impact

Over the last decades, humanity realized that not all resources are limitless and that our actions impact the environment. Growing consciousness regarding our environmental impact started movements of reducing this environmental impact in a wide range of industries. There is a lot of research on this topic. For the FRP jetty, the topic of sustainability needs to be researched. This section introduces topics related to the environmental impact of the jetty.

11.1 Life cycle assessment

The impact of structures and object on the environment can be done in many ways. For a decent comparison of different structures and objects, assumptions need to be formulated. A life cycle assessment (LCA) regards structures and objects over its entire life: begin-of life, usage, and end-of life (e.g. disposal). Within these life phases, several topics can be incorporated in the LCA. Among these topics include material usage, transportation, construction energy costs, impact of maintenance, release of chemicals to the environment, recyclability, etc.

When conducting an LCA, several input is required. The material types and quantities used in the construction is important. Also, information how these materials are produced and how they will be processed once the lifetime. With these parameters and an LCA database the assessment can be executed.
Databases with data regarding the environmental impact of materials are available online, such as the database provided by the University of Washington [43] and the Sirii Environmental Data Network provided by the Industrial Research Institutes in Sweden [44]. Also, an ISO standard exists which gives a framework for executing life cycle assessments, the ISO 14040/44 [5].
The CUR 96 highlight a few specific characteristics of FRP regarding its life cycle, which are shortly presented in the succeeding subsections.

11.1.1 Production phase of FRP materials

The main components of FRP composites are fibers and resin material. There is a wide choice of variety of these two components, which have different impacts on the environment.

The production of carbon fibers requires a significant amount of more energy than the production of glass fibers [5]. Natural fibers just as jute and flax fibers have a low environmental impact compared to carbon fibers and glass fibers.
The usage of epoxy resins has a far bigger impact on the environment than polyester resins [5]. It should be noted that this is only in terms of production. Section 10.2 noted that epoxies and vinylesters have a longer life time expectancy than polyesters.

In general, the manufacturing processes of FRP composites has a relatively small environmental impact [5]. However, this is only small if the emissions of chemicals are limited or treated.

11.2 Utilization phase of FRP materials

FRP structures are lightweight compared to structures made of steel and concrete. Therefore, transportation and installation requires less energy. Also, FRP is very durable and has an excellent resistance against external influences. This durability can be an inherent property if the composite is well designed. There are structures and products of FRP which are utilized for 30 y to 40 years, like minesweepers, electricity boxes, and cooling towers [5].

11.2.1 End-of-life phase of FRP materials

The type of resin, thermoset or thermoplastic, is very important for the end-of-life processes. This is because thermoplastics are very suitable for recycling processes, whilst thermosets are hard to recycle. At the end-of-life of a structure or product is reached if they can no longer fulfill their intended function or if the function is no longer needed.

At the end-of-life, several processes for FRP is available.
If the product is not yet broken or severely damaged but it is no longer needed for its function, the product may be reused. It may be reused in a different setting, giving it a different function. This is a suitable option for thermosets since they cannot be remodeled.
The FRP can be recycled. If the FRP product is going to be recycled, the fibers and the resin matrix need to be separated. Fibers which are incorporated by a thermoset matrix may in some cases be separated with chemical or thermal processes. Often the quality of the fibers deteriorate in these recycling processes.
The FRP can be grinded to small pellets and then it can be used as a filling material. For instance, it can be used in the core of reinforced plastic matrix piles (see Section 7.5.1). However, the pellets can also be used as fuel. For instance, in cement ovens, the resin material is burned as fuel and the glass fibers is used as a raw material to produce concrete [5].

11.3 Advantages of FRP Piles regarding the environment

Regarding long-term structural performance, composite piles may outperform traditional piling with respect to axial loading. The real main advantages is their low life cycle cost [4]. The cores of SRP piles (Section 7.5) can be made from recycled plastic. If the reinforcement fiberglass bars are also made from recyclable plastic, the pile is 100 % recyclable.
Zyka and Mohajerani collected advantages of composite piles regarding the environment from several research papers [4]:

- Resistance to corrosion, rot or deterioration in marine environments because the piles are not affected by marine borers.
- Treated creosote timber piles release chemical into the marine environment, which composite piles do not release. This enhances local marine wildlife.
- Chemicals used to treat timber piles will not affect workers during pile production and installation because FRP does not posses such chemicals.
- In addition to timber piles, FRP piles do not need intensive maintenance. This reduces life cycle costs significantly.
- The FRP piles can be fully recyclable in addition to wooden piles.
- FRP piles do not need additional chemical treatment because they inherently posses anti-corrosion properties. However, protection against UV light is needed. Resistance against deterioration due to UV light can be achieved by adding environment friendly additives which darken the color of the FRP pile.

They also note that further investigation of FRP is required in order to determine the negative effects of FRP piles in marine environments.

12 Costs of FRP

Two cost estimation methods of FRP composite are elaborated: determine the material costs and labor costs per produced kg of composite material and scaling reference products. This section estimates the costs of both cost estimation methods.

12.1 Costs of composites per unit weight

Van der Valk investigated the costs of FRP structures per kilogram of material; the results of his research are presented in Table 11.

Fiber and resin	Material costs [€/kg]	Mean base material cost [€/kg]	Labor costs [€/kg]	Total costs [€/kg]
E-glass and polyester	1.3 to 2.5	1.9	2 to 5	4 to 7
E-glass and vinylester	1.7 to 3.4	2.6	2 to 5	5 to 8
E-glass and epoxy	2.1 to 8.5	5.3	2 to 5	7 to 10
S-glass and polyester	10.2 to 13.9	12.0	2 to 5	14 to 17
S-glass and vinylester	10.6 to 14.8	12.7	2 to 5	15 to 18
S-glass and epoxy	11.1 to 19.8	15.5	2 to 5	17 to 20
Aramid and polyester	12.2 to 20.4	16.3	2.8 to 7	19 to 23
Aramid and vinylester	12.6 to 21.3	16.9	2.8 to 7	20 to 24
Aramid and epoxy	13.0 to 26.3	19.7	2.8 to 7	22 to 27
Carbon and polyester	7.0 to 30.1	18.5	2.5 to 6	21 to 25
Carbon and vinylester	7.4 to 30.0	19.2	2.5 to 6	22 to 25
Carbon and epoxy	7.8 to 36.1	22.0	2.5 to 6	24 to 28

Table 11: Overview of composite costs per kilogram for different combinations of fiber and resin [6]

12.2 Costs by reference products

Reference products can give a good indication of the costs if they have common areas with the designed composite. Such areas can be the fiber volume fraction or the manufacturing process.
Common structural elements When requested, BIJL provides a price list with up to date prices [7] of pultruded products. Table 12

Structural element	Area [mm^2]	Unit price [€/m]
BIJL I-profile	8213	107
BIJL plank 400x85	8951	114
BIJL U-profile	2752	33.6

Table 12: Overview of unit prices for BIJL products [7]

FRP piles
Zyka et al [4] presented the costs of different FRP pile types as can bee seen in Table 13. The costs per meter pile are presented in Australian dollars; this is converted to Euro by using an exchange rate of 1 $AUS = 0.6695 .

Composite pile type	Costs [$AUD/m]	Costs [€/m]
Concrete filled FRP pile	195	131
Composite steel pipe core pile	320	214
Reinforced plastic matrix pile	380	254
Fiberglass pultruded pile	N/A	N/A
Fiberglass reinforced plastic piles	390	261
Hollow FRP piles	165	111

Table 13: Costs of different FRP pile types from Zyka et al., estimated in 2016 [4]

13 The future of FRP

The usage of plastics in the way they are currently manufactured won't last forever due to the limited reserves of crude oil. Therefore, alternatives have the be innovated to substitute these products. For this reason, scientist are researching on manufacturing processes for plastics from renewable sources. These sources include bio-based products like soy, flax and jute. As always with the introduction of new materials, weaknesses have to overcome. In the case of bio-based plant products for the production of composites is this the low strength properties. In table 14 the material properties of some composites are presented to compare traditional composites with bio-based composites.

Material	E-Modulus [GPa]	Tensile strength [MPa]	Density [kg/m^3]
Short fiber composites			
Glass-filled epoxy (35 %)	25	3450	1900
Glass-filled polyester (35 %)	15.7	4300	2000
Glass-filled nylon (35 %)	14.5	2600	1620
Glass-filled nylon (60 %)	21.8	1800	1950
Unidirectional composites			
S-glass/epoxy (45 %)	39.5	3450	1810
Carbon/epoxy (61 %)	142	3450	1590
Kevlar/epoxy (53 %)	63.6	3450	1350
Bio-based composites			
Air laid flax fiber mat (40 %)	5	50	?
Air laid flax fiber mat(70 %)	9.7	78	?

Table 14: Material properties of a selection of fibers [2][8]

As we can see, the mechanical properties of the air laid flax fiber mat are significantly lower than that of traditional composites. This is a mayor drawback.

Madbouly et al. reviewed several fiber reinforced plant oil-based composites. In the research, it is stated that almost "lmost all of the studies in vegetable oil-based composites involve the use of petro -leum-based comonomers, so the composites matrix is not completely bio-based" [8] . They expect that in the future composites will be produced which will have a higher bio-degradable content and improved mechanical properties.

De Araújo speculated on the future of fibers [45]. He states that current products on the market have very short life cycles and are not designed for sustainability. He also foresees that in future manufacturing techniques, biological processes will play an increasing role. Regarding the application of bio-based marine environments, natural fibers have a huge disadvantages with respect to glass fibers. This is their low resistance to water damage. In an experiment, Apolinario et al. investigated the effects of water ageing on the mechanical properties of flax and glass fiber composites [40]. They concluded that the tensile modulus of glass-fiber reinforced composites was slightly effected by water uptake whilst the tensile modulus of flax-fiber reinforced composites experienced a reduction of 37 %. Also, they found that the ultimate stress of the flax-fiber reinforced composites increased by 34 %.

A main design challenge when applying FRP composites in the construction industry is dealing with a relative low elasticity modulus compared to high strength properties. Therefore, this is a challenge to overcome in improving bio-based composites.

13.1 Biobased pedestrian pridge example

In 2014, Gkaidatzis subjected his master thesis where he designed a bio-based FRP bridge [46]. The bridge is illustrated in Figure 39. Gkaidatzis researched numerous natural fibers, their costs and the technological viability of those materials. The research focused on the fibers and the bio-based polymers are not as extensively treated as the fibers. The bridge is mainly composed of basalt fibers and bio-based polyester resin and measures 15 m long and 2 m wide. The design life of the bridge is very long and a it is estimated that it will last for at least 100 years [18]. A cooperation between the Delft University of Technology, FiberCore Europe and Schiphol Logistics Park realized the design and the manufacturing of the bridge.

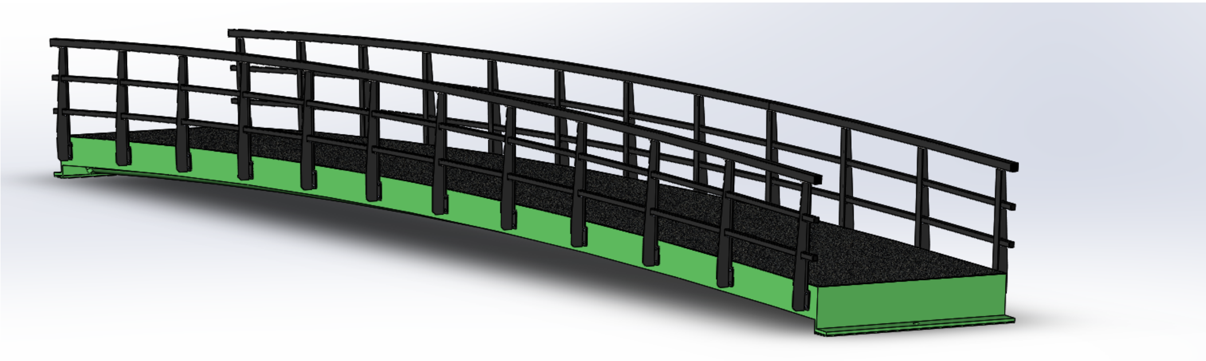

Figure 39: Design of a bio-based composite bridge [18]

14 Conclusions

14.1 Conclusion

The aim of this literature study was to get familiar with the subject of FRP and to find possible challenges when designing a jetty from FRP. In general, sufficient knowledge is gained in order to start the technical design of the FRP. Topics such as material properties, manufacturing techniques, mechanics, structural design, and joints have been explored. This literature study concludes with a list of identified challenges and blind spots.

The research questions stated at the introduction of the literature study are repeated here:

1. What is FRP?
2. What are the advantages and disadvantages of FRP?
3. What are the material properties of FRP?
4. What knowledge regarding mechanics is needed to design FRP composites?
5. How is FRP material produced?
6. In which hydraulic structures is FRP already applied?
7. Are there already FRP jetties and what are their characteristics?
8. What guidelines are available for engineering with FRP in civil engineering?
9. What are the durability properties of FRP? (reparations, life expectancy)
10. What are the sustainability properties of FRP? (C02 emission, recyclability)

Challenges of designing an FRP jetty
The following challenges are identified:

- In civil engineering structures where FRP is applied, Serviceability Limit State criteria are often more decisive for the dimensions of the structural elements instead of the Ultimate Limit State criteria
- No other FRP jetties of significant size have been found (i.e. commercial jetties other than providing a support platform for pedestrians)
- The low stiffness of the FRP material may induce unanticipated problems in the foundation of the FRP jetty in areas such as buckling resistance and pile installation

Blind spots
Not all research questions were answered satisfying: mainly the durability and sustainability properties of FRP in civil engineering applications were not answered.

Whilst plastics have found to be very durable in applications in other industries, a minimum reference projects were found where FRP structures outlasted their intended life time (50 to 100 year). Therefore, no hard evidence is available for the claims of manufacturing companies and advocates of FRP structures regarding the durability properties of FRP in civil engineering structures.

The sustainability argument is often forwarded from the expected lifetime of FRP structures, hence its durability properties. Therefore, the same reasoning of the preceding paragraph is valid with respect to the sustainability argument as well: the lack of reference cases fulfilling their intended life time doesn't provide the sustainability claims of FRP a strong basis.

The life cycle costs of FRP structures are not well known. Arguments which rest on durability claims state that the life cycle costs of FRP structures will be lower since less maintenance is required. However, it is not unthinkable that still frequent inspection is required in order to at least guarantee the structural integrity of the jetty.

14.2 Discussion

Depth of the literature study
The main body of this literature study is limited when regarding to the subject of FRP. This is mainly, because the author of this literature study had no experience in composite design. In order to design a jetty in FRP, and introduction and expansion of knowledge was required.

Additional research during the thesis
During the elaboration of the thesis subject, additional literature review is done due to encountered knowledge gaps. The main topics which were further researched were the buckling of laterally unsupported FRP piles and the driveability of FRP piles.

Choice of guidelines
While several guidelines were presented in this literature study, the CUR96 was chosen as the definite guideline in the scope of this thesis. A reason for this is because this is the most up-to-date design guideline available yet. Also, it is a Dutch guideline and hence convenient for Dutch applications, as will be the elaborated design in the accompanying thesis of this literature study.

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