Feasibility study for FRP in large hydraulic structures

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1 Introduction

1.1 Hydraulic structures
The Netherlands, as a low lying country, has to deal with a great deal of water, such as the North Sea and other waterways. The land has to be protected against flooding. Especially low lying areas are very vulnerable to flooding. This occurs due to high water levels in rivers, lakes, canals and seas. There are several possibilities to protect these areas against flooding. For example the ground level can be increased, or a water barrier can be constructed. When a water barrier is made, a close defence system needs to be built. A close defence system is built from a range of barriers like dunes, dikes and hydraulic structures. Not only does the land need to be protected against the water, water can also be used to our advantage, for example as a means of transportation. Different waterways which have different water levels, but cross each other, can be levelled out by the use of a specific hydraulic structure, the lock.

When hydraulic structures are used to close a waterway for protection or open a waterway to enable transportation a movable hydraulic structures can be applied. In normal situations enabling transportation is preferable, but at the same time when a storm is present we want to close the waterway to ensure that the land doesn’t overflow. In order to secure both goals, a structure is required that can be opened and closed at all times. Often a hydraulic construction will have a gate to make sure that this is possible.

1.2 Problem description
In this thesis the problem of hydraulic structures with a lifting gate will be considered. Up till this moment, many storm surge barriers and locks are equipped with a lifting gate. These gates should have a reduced dead weight, for the mechanism to be capable of lifting the gate. When the gate has a higher dead weight, a mechanism with a higher capacity is required. Therefore most lifting gates are built from steel, because these steel has a high strength to weight ratio.

A lifting gate is exposed to heavy weather influences and is affected by water it may come in contact with. For steel gates corrosion is therefore inevitable. To prevent the gate from corroding, the gate has to be treated with a coating. This will be done during maintenance periods. Due to strict environmental requirements, a tent is set up around the gate, which prevents that paint residues subside into the sea. The precaution of setting up a tent and recoating the structure incurs enormous costs. Therefore, it would be cost-effective to find a way to build a maintenance friendly gate.

1.3 Problem definition
The current lifting gates of storm-surge barriers or large locks are made of steel and their use comes with high maintenance costs.

1.4 Objective
The objective of this study is to investigate the possibility to build a lifting gate of fibre reinforced polymer (FRP). The material FRP is still under development, but has shown its potential in the aerospace and maritime sector. A few advantages of this material are the high strength/weight ratio and the low maintenance costs.

In this feasibility study there will be looked at the technical possibilities of FRP and a life cycle analysis will be done, in which a cost comparison will be made with a steel gate.
The objective is to design a cost competitive structure. It is necessary that during the design process this has to be kept in mind. The choice of fibres is important and there will be looked how a FRP structure can be built up out of segments. So that there is no specific mould needed for this project.

1.5 Work approach
This master thesis consists of a feasibility study of a lifting gate of a storm surge barrier or lock made of FRP. This thesis consists of two parts, a literature study and a case study. The literature study starts with an introduction about FRP. In this literature study the basic information of the FRP material, the applications of FRP in structures, determination of mechanical properties and different types of joints will be discussed.

In the design study, the information of the literature study will be used to construct a design for a gate of FRP. Therefore the program of requirements needs to be set. After this some variants can be designed. These will be developed, so that the rough dimensions are known. With a Multi-Criterion-Analysis (MCA) a decision for the best option will be made. This variant will be developed into a final design. This final design will be modelled in a Finite-element program. A specific interest will be placed at the details at connections of the segments.

This report consists of the literature study. In chapter 2 the developing of FRP structures is described. Chapter 3 gives an overview of the material. In chapter 4 the different manufacturing processes are described. Chapter 5 gives a method to estimate the material properties of a FRP. In chapter 6 different codes and guidelines are summated. Chapter 7 gives advises for a design. Chapter 8 is an overview of the applied joints in FRP structures. In chapter 9 are the costs of the different fibres, resin and combination estimated. Chapter 10 gives the conclusion, with the possibilities for the case study.
2 Development of FRP structures

2.1 History
The today’s composite industry is born with the first introduction of the first thermosetting plastics in 1909. This was phenolics. However, the structural composite industry really starts to rise in 1940. The first range of thermo settings resins where introduced in the UK, in 1946. These hot cured resins where not user friendly, but made a possibility to make a production of low pressure mouldings of great strength, with a relative cheap and simple production process. The developments were fast, so the first British cold-curing polyester resin was introduces in 1947. Until then the main commercial use of FRP’s was for the construction of the aircrafts of the USA from about 1942. At the same time developments were made for the polyester resins, so the attentions were switched to the reinforcements. At the beginning FRP was applied in technologies where the costs were not the most critical part. From 1947 there work on more economically forms of reinforcements, other than woven cloth chopped strand mat (CSM). The right reinforcement and for the right price followed rapidly in the early 1950s, by the development of the FRP boat hulls, FRP car buddies and the FRP lorry cabs. [6]

Around the 1950’s there was a growth of FRP material. It took some time to develop FRP for the civil engineering industry. The use of FRP composites in constructions can be divided into specific areas. These areas will be discussed from there utilisation advantages and there limitations. [6]

2.2 Developments of FRP in civil engineering

2.2.1 Composite cables
FRP materials are well-known due to their high strength capacity. This property is the main reason to use FRP in cables for stay bridges or tendons. The high resistance of composite cables against corrosion provides significant lower maintenance cost. Due to their low self-weight, the handling costs and transportations costs are low. To maintain the maximum tensile strength of the cable, the strands mostly places parallel to each other. [6]

A design issue for composite cables is how to make use of the total tensile strength. The conventional anchor systems for steel cables cannot be applied, due to their relative low lateral properties. With the development of new anchor systems composite cables can achieve 90 per cent of their ultimate tensile strength. [6]

2.2.2 FRP reinforced concrete
FRP reinforced concrete can be applied in different forms. Short fibres are applied in concrete. This can be effective to limit cracking. But significant increase of the load-bearing capacity cannot be achieved. [6]

The use of FRP reinforcing bars are mainly applied in Japan and Canada and for a smaller extent in the USA and Europe. The reinforcing bars are mainly made of glass-fibres, due to there lower costs. There are some uncertainties for the durability, because of alkali resistance and the possible stress rupture in cracks. Problems can occur due to large temperature strains. The weight of the FRP bars are lower than concrete, before the concrete is cured the FRP bars needs to be protected against floating. [6]
FRP is also used as tendons in prestressed beams. Some advantages for carbon FRP tendons compared with the traditional steel tendons are: [6]

- High corrosion resistance
- High strength/self-weight ratio
- Small prestress losses in tendons, especially due to relaxation
- Fatigue resistance

The future of FRP prestressing cables is for a large part dependant of the anchoring technology. These products have still the following disadvantages: [6]

- Limited degree of prestressing (50-60 % of failure strength)
- Danger for corrosion between the carbon wires and the metal sheaths.
- Less information about the long-term behaviour
- Less information about the costs

### 2.2.3 Pultruded profiles

Most applied beams and girders that are made from FRP are copies or variations of steel beams. The profiles used in the civil engineering are primarily produced with pultrusion. There are in principle no limits for the dimensions of the elements. The main limitation is not dependant of the manufacturer, but the process off curing of the resin exothermic. This can give distortions for discharging the heat for large thickness and in extreme cases combusting. Most popular are the glass FRP profiles, figure 1 gives an overview of different pultruded profiles of the manufacturer Fiberline in Danmark. [14]

![Figure 1: Overview different profiles](image)

2.2.4 Bridge deck systems

The majority of the applied deck systems are made with the pultrusion technique. With this technique the height of the deck is constant and limited to about 225mm. This gives maximum spans of around the 2.7m. Different techniques like gluing, bolts or dowels can be used to combine these elements. [6]

Other elements can be made by infusion technique or hand-laminating. These elements have the advantages against pultruded sections like the plate thickness is variable. So this gives the possibility to make larger spans and a cross slope. Most of these elements are made of sandwiches, this are structural elements with a concentrated mass in the surface layers and with a low density core. These structures are characterized by their high stiffness to weight ratio. Some advantages are the low dead weight (20% of a comparable concrete slab), high fatigue strength and the large corrosion resistance. Due to their low dead weight, they can be easy applied. An overview of different deck types is given in figure 2. [6] [14]
2.2.5 Full composite bridge structures

The full composite bridge structures consist of a superstructure which is constructed of FRP materials. The substructure, like the piers and abutment, are mostly still made of traditional materials. Full FRP bridges can be divided in traditional bridges with material substitution and bridges with new material concepts. [6] [14]

Substitution of traditional materials

The substitution concepts are applied since the 1980s. The first bridges that are made in FRP are mostly pedestrian trusses and beam bridges which are made up of pultruded FRP profiles (see figure 3). The connections between the profiles are usually bolted. There are also bridges built with the classical girder-slab system. The girders are mainly built of pultruded profiles and the deck is made of the deck types as mentioned in the paragraph 2.2.4. [6] [14]
Material adapted all-composite bridge concepts
Since the 1970s China has done experiments with the application of FRP in bridge structures. They built the first highway bridge, the Miyun bridge, in 1982. The Miyun bridge is a single span bridge with a length of 20.7m and consists of six hand-laminated girders. The bridge is designed for a maximum truck load of 30 ton. [14]

In the Netherlands the first composite heavy load class 60 bridge is built in 2010 by Fibercore. This bridge has a span of 12m and a width of 11,2m. Figure 4 shows a photograph of this bridge, the cables between the pylon and the bridge deck are only placed for architectural purposes.

2.2.6 Hybrid new bridge structures
Hybrid bridge structures are structures that are built with a combination of materials. This can be a bridge of the traditional materials in combination with FRP elements. The most common hybrid structure is a bridge with girders made of traditional materials and a deck built of FRP elements. [6]
In hybrid structures a part of the traditional material is replaced by FRP elements. Apart from these there are also some material adapted hybrid structures. The University of California developed a carbon shell system which consists of tubes that are made of thin walled filament carbon fibres. These tubes are filled with concrete, and have the function of reinforcing and formwork. The University of California have also developed the hybrid tube system. This system consists of pultruded rectangular hollow sections with prefabricated carbon fibre shear stirrups. Between the girders a prefabricated FRP from panels are placed, which is the formwork for the fibre reinforced concrete slab. [1][6]

The Space System is developed by the Maunsell structural Plastics in the UK. This system consists of a steel frame with a conventional deck, made of steel or concrete. They are enclosed by jointly load bearing skin which is made of the ACCS system. This system gives also protection against the weather. Significant innovations in this system are the shear connectors, which provide for an integral system. [1][6]

In the Netherlands the most known hybrid bridge structure is operated in April 2012. This bridge consists of a truss bridge with a length of 140m. The bridge deck is made of composite and has been assembled of seven segments. The composite deck is joined to the steel truss with glue and bolts. The bridge needed to be of low weight, therefore a truss structure with a composite deck is applied. In figure 5 the seven composite parts are schematized, and a photo of combining the deck and truss is given. Figure 6 gives an overview of this bridge. [27]

![Figure 5: Left: the composite parts; right: composite deck is joined to the truss][27]
2.2.7 Building structures
There are a lot of possibilities of applying FRP in the building industry. The earlier mentioned pultruded profiles and the deck can be used as floors in buildings. The possibilities of FRP in building structures are shown in the Eyecatcher Building in Basle, this building is built during the Swiss Building Fair in 1999. The Eyecatcher Building is a multi-storey framed building and was a demonstration of the potential of using FRP profiles in the building industry. The primary structure consists of three parallel trapezoidal frames which are connected by wooden decks. The two outer frames are integrated with the facade. See figure 7 for a photograph of this building. [1][6]

2.2.8 Lock doors
In the civil engineering industry FRP is mainly used for bridge structures. In the Netherlands are already some developments of using FRP constructions in the section of hydraulic structures. In 2000 the Spieringssluis was the first lock door in the Netherlands. As can see in
figure 8 the structure looks identical to a steel lock door. In 2012 a FRP lock gate is applied for the waterway Erica-ter Apel, this gate is built up with a sandwich structure.

![Figure 8: Left: Spieringsluis(2000), right: Lock door waterway Erica-ter Apel (2012) [26]](image)

2.3 Applications of FRP in other markets

2.3.1 Aerospace

The Aerospace industry was the first industry where FRP is applied. Composites made of glass, carbon or kevlar fibres are designed for aerospace parts. The primary purpose of FRP materials in the aerospace is their very good weight to strength ratio.

In military aircrafts FRP components are used for the stabilizers, wing skins, flaps, fin boxes and various other components. The mass reductions that are reached for this components range between the 20 and 30%. The aerospace primarily uses carbon fibres, cause of their excellent material properties. [10]

The mean reasons for the spacecraft industry to apply FRP components are also weight savings and dimensional stability. For spacecraft articles that are in low earth orbit, with a temperature variance from -100 to +100 °C is it important that to maintain dimensional stability in the structural as well in the reflecting members. Laminates built up of carbon and epoxy can be designed with a zero thermal expansion coefficient. Typical space structures are facesheets, tubular truss structures, antenna reflectors etc. [10]

The Airbus A380 contains parts of fibre metal laminates(FMLs). FMLs are multicomponent materials which are utilised of metals, fibres and a matrix. FMLs are produced by stacking alternating layers of metal foils and matrix resin. In the 1980s FLMs where developed by Vogelsang at the TU Delft, which consists of aluminium sheets and prepregs made of aramid fibres and epoxy and is known as ARALL (Aramid Reinforced ALuminium Laminte). In 1991 the aramid fibres are replaced by glass fibres, which is called GLARE(GLAss Reinforced FML). This material is used for the Airbus A380, see figure 9 for an overview of the GLARE parts in the airplane. Glare is quite expensive to produce and the part size are limited due to the required prepreg and the use of a autoclave for the manufacturing process. [24]
2.3.2 Wind turbines

Composites have found their way in wind turbines for many years. The main parts of a wind turbine, the blades, are made of composites. Blades of composites are intensively used due to their low weight and high fatigue resistance. The blades of a wind turbine have an elongated shape. The blade consists of a load-carrying beam, which is covered by an aerodynamically shaped shell. The aerodynamically shaped shell is made of a sandwich structure, to save weight. The load carrying parts have to resist high fatigue loads and are therefore made of glass fibre/polyester or carbon fibre/epoxy. A common manufacturing method is to make two shells in external moulds. A load carrying beam or webs is placed between the shells and bonded together. The largest part of the blade consists of sandwich structures. The blades have to be fitted to the nacelle, so close to the roots changes the shape in a circular tube. Figure 10 gives a schematization of two common design principles. Figure 11 shows the injection process in the mould and the combining of the two parts. [19]
2.3.3 Maritime

Since the 1960s composite structures have found their way in the recreational boating industry. After 20 years of development work, the manufactures have made a mass produce for easily maintained hulls, which are made of a minimum number of assembled parts. The earlier FRP structural designs worked with trial and error, which has led to a high attrition rate of start-up builders. [12]

Almost all marine constructions are done with a female mould and finished with a gel coat surface. The hull is mainly made with the hand-lay up method or with vacuum-injection method to get better fibre volumes. The manufacturing of the moulds are major investments for the companies. On this way boats with a length of 40m are made. Figure 12 shows the construction and the storage of a female mould. (artikel)
3 Materials

3.1 Introduction
A composite is defined by a material which is made of two or more materials. The properties of the composite material are different than the components. FRP composites are a combination of a resin and the reinforcement. The resin is to bind the structural fibres of the reinforcement together. In the following section these base materials of a FRP will be discussed. [14]

3.2 Reinforcements
The reinforcement in a composite consists of fibres. These fibres consists of thousands filaments with micro diameters. These fibres can be separated in different forms. In a lot of applications the fibres are indefinitely long, this is called continuous. There are also short fibres with a length of 10 to 50 mm. These fibres are used in the spray up method (see paragraph 4.2.3). The reinforcement fibres are made of carbon, glass or aramid (see figure 13). These materials will be discussed in the following sections. [8]

![Figure 13: The most common fibres, left glass fibre; middle: carbon fibre; right: aramid fibre][30]

3.2.1 Forms of fibres

3.2.1.1 Rovings
Continuous filament rovings are directly made from the melt spinning of glass. Rovings are usually made by collecting individual fibres, they can form a strand of fibres by winding them together. The spool size and the number of strands that are used depend on the end use. Continuous filament rovings are used in the pultrusion, filament winding and weaving processes. [6]

3.2.1.2 Mats
For planar reinforcement are mats the cheapest solution, but for unidirectional rovings they are more expensive.

Chopped strand mat (CSM)
Chopped strand mat consists of a chopped roving mat which is dispersed uniformly over a mat. The loose fibres will be bonded with a binder. These binders are built up of two forms, emulsion and powder. The emulsion is based on a polyvinyl acetate emulsion and the powder is based on a bisphenol polyester powder. The binder consists of 3-6% of the total weight. The weight of CSM ranges between the 225-900 g/m². [6]
Continuous filament mat (CFM)
Continuous filament mat is produced on the same way as CSM. The chopped rovings fall on a conveyer belt and form multiple layers. Here a binder is added and the mats consist of multiple layers. [6]

3.2.1.3 Fabrics
Fabrics are lighter weight materials which are constructed of woven yarns, fibres or filaments and usually for a planar structure. Typical glass fibres are built of woven warp yarns or fill yarns. These fabrics can be woven into a variety of styles. Woven fabrics are available in a number of different weaves, for example (see figure 14 for an overview): [6]

- Plain weave
  In this weft each warp is successively above and below each other. This is the oldest and most common weave technique in the textile industry. The strength is uniform in both directions, because in both directions the same amount of fibres is used.

- Twill weave
  The way that the warp and weft pass over each other can vary. Figure 14 illustrates the examples of a 3 on1 and a 2 on 2 weave.

- Satin weave
  For the satin weave one warp is woven over several yarns and then under one yarn. When a configuration is passing four yarns and over one yarn is called a five-harness satin weave. The higher the satin number is, the higher the warp and weft threads. Satin weaves are less open than other weaves, which causes higher strength in both directions.

- Unidirectional weave
  With the unidirectional weave, a lot of yarns are placed in one direction and less yarns in the other direction. This gives the maximum strength in one direction.
3.2.2 Glass fibres

Glass fibre reinforcement is available in a variety of forms. Glass contains of primary metallic oxides. The largest single compound in glass formulations is Silica (SiO$_2$), which takes 50-70% of the weight of the glass to its count. There are different grades of glass fibres. They are identified by the following letters. E-glass stands for electrical glass and is the most commonly used glass fibre. A(Alkali)-glass was the common base material before the E-glass. C(corrosion resistant)-glass is used in specialized products in the structural engineering. S-glass stands for structural or high strength glass, these is used to produce high strength fibres and is primarily used in the Aerospace industry.

3.2.3 Carbon fibres

Reinforcement of carbon fibres have an excellent performance and are light weighted. The strength of carbon fibres is higher than glass fibres and also the stiffness and fatigue resistance is higher. So the properties of carbon fibres are ideal for structural purposes. The main disadvantage of carbon fibres are the relative high costs and the energy requirements for the production. Due to their light weight are carbon fibre often used in aerospace applications.

3.2.4 Aramid fibres

The fibres of the first generation FRP tendons were made of aramid fibres. This was in the 1980s in Japan and Europe. Now are the aramid fibres primarily used in application to strengthen columns or to fill the fibres of a unidirectional glass or carbon fibres. Aramid fibres are less attractive for structural purposes, cause of their high price, high moisture absorption, difficult to process and there low compressive properties. The main advantages are their toughness and high strength. Aramid FRP is applied on locations where energy absorption is needed, like a bulletproof vest. They have a yellow colour and the costs are...
similar to carbon fibres. The longitudinal fibre strength ranges between the 3400-4100 MPa.

[8]

3.2.5 Other reinforcements
The reinforcement’s glass, carbon and aramid are the most common used to manufacture a FRP. However, there are some other reinforcements applied over the years. Some examples are:

- Polyester fibres, these are used to manufacture surface tissues and for structural purposes where high impact resistance is needed.
- Jute fibres, the main reason of their application are: cheap, readily available and naturally occurring fibres which are used in woven cloths.
- Sisal fibres, these are also cheap and naturally occurring fibres which are used in phenolic based DMC’s, but rarely with an epoxy resin.
- Nylon, these are used to reinforce an epoxy resin and have a high impact and chemical resistance. There are mainly used in combination with glass fibres.
- Boron, these are used to reinforce epoxy resins for applications in the aerospace industry. There are expensive, which limited its use. [6]

3.2.6 Summary reinforcement properties
An overview of different approximate properties of the different type of fibres is given in table 1. The stress-strain relation of different fibre types is given in figure 15.

![Figure 15: Stress-strain relations until cracking occurs of different fibres types.][4]


<table>
<thead>
<tr>
<th>Fibre</th>
<th>Density $\rho_f$ [kg/m$^3$]</th>
<th>Elastic modulus $E_f$ [GN/m$^2$]</th>
<th>Tensile Strength [GN/m$^2$]</th>
<th>Max. Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>2540</td>
<td>70</td>
<td>1.7-2.7</td>
<td>2.4-3.7</td>
</tr>
<tr>
<td>S</td>
<td>2490</td>
<td>85</td>
<td>2-3</td>
<td>2.3-3.5</td>
</tr>
<tr>
<td>Carbon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM</td>
<td>1800</td>
<td>220-240</td>
<td>3.5-4.5</td>
<td>1.5-1.9</td>
</tr>
<tr>
<td>HT</td>
<td>1800</td>
<td>250-300</td>
<td>4.4-5.0</td>
<td>1.5-1.8</td>
</tr>
<tr>
<td>HM</td>
<td>1850</td>
<td>360-420</td>
<td>2.0-3.0</td>
<td>0.5-0.7</td>
</tr>
<tr>
<td>Aramid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HM</td>
<td>1450</td>
<td>130</td>
<td>3.0-3.5</td>
<td>2.3-2.6</td>
</tr>
</tbody>
</table>

Table 1: Approximate properties of common grades of fibres [4]

3.3 Resins

3.3.1 Introduction
In the composites industry is the term resin used to refer to the polymer ingredient of the non-fibrous part in a FRP. This non fibrous part is also known by the term matrix. In a FRP have the fibres the load-bearing function, but without a resin they have no structural integrity. The resin has the following four essential functions:
- Bind the fibres and form the geometrical shape
- Transferring the load to the fibres
- Give the material buckling capacity
- Protecting the fibres from external influences.

There are two basic materials distinguished, which are used to form the resin: thermoplastics and thermosets. A specific property of a thermoplastic is that they are softened when they are heated. When the temperature decreases the thermoplastic becomes again hard. With this property thermoplastics can be made in every form when they are heated. But for structural purposes this property has some negative aspects. Thermosets are produced with a polymerisation reaction or hardening. In contrary to the thermoplastics, thermosets can after hardening no longer be formed plastically. The most important resins are: polyester, vinyl ester and epoxy. These resins are discussed in the following sections. [1][6]

3.3.2 Polyester resins
The most frequently used resins are the unsaturated polyester resins, usually called polyesters. The polyester gives the composite all-round properties. The polyester is a syrup that consists of polymer chains. These chains are dissolved in a reactive organic solvent. With the application of a catalyst and an accelerator, the syrups can react in a cold state without pressure to form the final structure. [6]

3.3.3 Vinyl ester resins
Vinyl esters are better resistant against corrosion and have better thermal properties than polyester resins. The vinyl ester has also better elongation properties, so it is better resistant against impact loads and fatigue. The vinyl ester can be considered as an extension of polyester. The vinyl ester is also supplied in a reactive monomer. The most important part is the bisphenol epoxy structure. [6][13]
3.3.4 Epoxy resins
The epoxy resin is primarily used in carbon fibre structures. The use of the epoxy resin will result in the best mechanical properties. The main reasons are: cured epoxy systems are resistant against moisture and chemicals and provide great electrical insulation properties. When the material is cured above the service temperature, the temperature stability is high. [6]

3.3.5 Other Thermosetting resin systems
The three mentioned resins are the most common applied resins. Beside these also other thermosetting resins are used for the laminating and moulding applications. These resins will only be mentioned here. These other resins are:
- Furane
- Polymide
- Silicone
- Phenolics
- Melamine
- Urea-formaldehyde.

<table>
<thead>
<tr>
<th></th>
<th>Density $\rho_f$ [kg/m³]</th>
<th>Tensile Modulus [GPa]</th>
<th>Tensile Strength [MPa]</th>
<th>Max. Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>1200</td>
<td>4.0</td>
<td>65</td>
<td>2.5</td>
</tr>
<tr>
<td>Epoxy</td>
<td>1200</td>
<td>3.0</td>
<td>90</td>
<td>8.0</td>
</tr>
<tr>
<td>Vinylester</td>
<td>1120</td>
<td>3.5</td>
<td>82</td>
<td>6.0</td>
</tr>
<tr>
<td>Phenolic</td>
<td>1240</td>
<td>2.5</td>
<td>40</td>
<td>1.8</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>varies</td>
<td>2.9</td>
<td>71</td>
<td>5.9</td>
</tr>
</tbody>
</table>

*Table 2: Approximate properties of thermosetting polymer resins [8]*

3.3.6 Thermoplastic resins
Next to the use of thermosetting resins, there is a great interest in the use of thermoplastic resins. Thermoplastics are tough, elastic and corrosion resistance. But have fundamental disadvantages against thermo settings, because of they soften above their melting point. They are viscous under molten conditions and in finished state they have a lower heat resistance than thermo settings. At these moments the use of thermoplastics for a resin is no option. [6]

3.3.7 Resin comparison
The three resins polyester, vinyl ester and epoxies are accountable for 90% of all thermosetting resins that are used for structural purposes. Table 3 gives some advantages and disadvantages of these resin types.
### Resin type

<table>
<thead>
<tr>
<th>Resin type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>Easy to use</td>
<td>Moderate mechanical properties</td>
</tr>
<tr>
<td></td>
<td>Lowest cost of the available resins</td>
<td>High styrene emissions in open moulds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High cure shrinkage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limited range of working times</td>
</tr>
<tr>
<td>Vinyl ester</td>
<td>Very high chemical and environmental resistance</td>
<td>Post curing required for high properties</td>
</tr>
<tr>
<td></td>
<td>Higher mechanical properties than polyesters</td>
<td>High styrene content</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Higher cost than polyesters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High cure shrinkage</td>
</tr>
<tr>
<td>Epoxies</td>
<td>High mechanical and thermal properties</td>
<td>More expensive than vinyl ester and polyester</td>
</tr>
<tr>
<td></td>
<td>High water resistance</td>
<td>Critical mixing</td>
</tr>
<tr>
<td></td>
<td>Long working times available</td>
<td>Corrosive handling</td>
</tr>
<tr>
<td></td>
<td>Temperature resistance up to 140°C wet / 220°C dry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low cure shrinkage</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3: Overview advantages and disadvantages different resin types [28]*

### 3.4 Cores

Composites are in a lot of constructions used as sandwich products. There are a few reasons to use a core in the FRP product. The main reason is to get the structural elements in the outer skins, which can take the bending moment. The middle part has only to deal with the shear force. To reduce the deadweight and the costs a core is used. Table 4 gives an overview of the relative bending stiffness and strength of a FRP material, when a core material is applied.

The core material is available in three forms: [6]
- Basically lightweight
- Lightweight because of foamed
- Lightweight because honeycombed

<table>
<thead>
<tr>
<th>Relative bending stiffness</th>
<th>1</th>
<th>7,0</th>
<th>37</th>
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</thead>
<tbody>
<tr>
<td>Relative bending strength</td>
<td>1</td>
<td>3,5</td>
<td>9,2</td>
</tr>
<tr>
<td>Relative weight</td>
<td>1</td>
<td>1,03</td>
<td>1,06</td>
</tr>
</tbody>
</table>

*Table 4: Schematization of relative bending stiffness and strength, by use of a low density core material.*

### 3.4.1 Foam

Foams are extensively used in FRP structures. Foam can simply be used as a non-structural support part to design the desired shape, or foam can be used for more efficient applications like the core of a sandwich construction. In the sandwich construction also low-
density foams maybe used, but always needs some resistance against pressure. For these structural foams good compression capacity and shear rigidity are required. [6]

3.4.2 Honeycombs
The first honeycombs were made by the Chinese of paper some 2000 years ago. The honeycombs are introduced in the aerospace industry around 1940. Honeycombs are made of a thin-sheet material and formed together in a way that looks like the honeycomb. This gives the material that has high properties in compression and shear. Honeycombs can be made of aluminium, aramid, fibreglass, Kraft paper, graphite and Kevlar. [6]

3.4.3 Solids
The most used solid cores are made of wood. For light weight structures balsa is still used, but synthetic materials are now superseding this. Syntactic foams core materials like bonded micro spheres of inorganic materials, ceramics, glass are used.

3.5 Gel coats
Gel coats are particularly produced by hand laminating and are used to give a decorative protective surface finish. The base resin is important to get a good performance for the gel coat. Pigments are added to give the gel coat the desired colour. The choice of the pigments can influence the viscosity and sometimes the cure behaviour of the final gel coat. To improve the handling properties, there can be a variety of additives added. They have to be carefully chosen, so that the additive matches with the pigments. The dispersion of the pigments in to the base resin is a critical step in the gel coat production. [6]

3.6 Creep
The deformations of a material in time are associated with the creep and relaxation response. Creep is the permanent deformation due to a load which is applied over a longer time. This phenomenon is normally undesired and limits the lifetime of a material. The inverse of creep is stress relaxation. The material is subjected to a constant strain which causes a reduction of stresses over time. [3]

The behaviour of a FRP due to creep depends of the structure of the material, fibre orientation and fibre volume fraction. However creep behaviour is particularly dominated by the resin properties. Unlike the conventional materials like steel and concrete, FRP’s are more vulnerable to creep during the manufacturing, due to the applied resin and adhesive. [3]

Creep in polymers is recoverable when the load is removed for low strains. The period between that the load is removed and the strain approaches zero is called the recovery period. See figure 16 for a creep response graph. [3]
3.7 Fire resistance

When a composite is exposed to high temperatures like 100 °C, the polymer resin will soften. This can cause distortion, buckling and failures to the load bearing structure. The need to use low-cost materials in civil engineering applications causes the use of expensive fire protective coatings or flame retardant polymers. [3]

Many polymer composites have a high flammability; especially the most often used polymers in the civil engineering (like polyester, vinyl esters and epoxies). So when there is a high fire safety needed, it may be necessary to increase the flame retardant properties of the resin. There are many ways to improve the fire properties of a FRP; the most common are chemical modification of the resin or adding flame retardant particles to the resin. [3]

The simplest way to reduce the flammability of composites is to add flame retardant fillers to the resin. The fillers particles are blended and added to the liquid resin. These particles must be uniformly distributed to ensure the fire properties of the final product. In most polymers is a content of filler required of 50-60 % of the resin. [3]

3.8 Fatigue behaviour

Fatigue is defined by the phenomena that cause damage and failure on a structure due to load cycles, even if this load is not high enough for any failure in the first cycle. Fatigue is measured as a number of cycles which give failure for a certain load level. Composites may under fatigue loads experience some micro cracking, fibre fracture, delaminating and microbuckling. These failure modes will interact and accumulate under fatigue loads. The material will lose resistance capacity or even will fail. [3]

The performance of a FRP during a fatigue load is affected by the type of fibres, fibre orientation and fibre lay-up. The most important part of the fatigue life is the fibres properties. In general it can be said that a laminate with a higher modulus have a higher fatigue strength. [3]

The matrix can also affect the fatigue properties for axial loads. For the unidirectional laminates is the effect of the matrix reflected in the failure mode. When the ductility of the matrix is higher than the fibres, than fibres will fracture multiple times over the length. The overload goes through shear over the matrix to the adjacent fibres. If the ductility of the matrix is lower than the fibres, the matrix will crack due to bridging of the fibres. [3]
The main damage mechanism for fatigue resistance is fibre dominated. The composites fatigue resistance is also influenced by other factors like: manufacturing process, history of the loads and the service environment. Regulations to calculate the fatigue resistance of composite are given in paragraph 6.4.4. [3]

4 Manufacturing process

4.1 Introduction
In the previous section the base materials of a FRP are described. The final properties of a material are dependant of the different choices that has to be made. Which fibres, resin will be applied, would there be a core material. In which direction are the fibres placed. This are all material aspects of a FRP. The final material properties are also influenced by the manufacturing process. [6]

The choice of a manufacturing process depends on the form, complexity of the product, repetition, costs and the required properties of the final product. In the following section the most commonly manufacturing processes will be discussed.

The process elements for a FRP can be given with the following steps:
- mixing resin and activator
- dispensing resin into mould
- curing
Adding reinforcement gives the following extra steps:
- Positioning reinforcement
- Impregnating reinforcement with resin

4.2 Open mould process

4.2.1 Hand laminating
Hand laminating is the oldest composite manufacturing technique. It is a labour intensive product, because the liquid resin is applied in the mould. After this the fibre are placed manually on the resin. With a laminate roller the fibres are impregnated and the air is removed. This process is repeated until the final thickness is reached. Some disadvantages of the hand laminating process are the inconstancy in quality of the products and the low fibre fraction. [14]

4.2.2 Saturation
Saturation is the first step to mechanization of the open-mould lay up. The resin is mixed mechanically and sprayed on the mould. The modern spray guns use air drive pumps, with a catalyst pump linked to it. These pumps deliver the resin to a hand-held trigger operation gun. With saturation the resin mixing is improved, but the distribution process is still handmade. [6]
4.2.3 Spray up
In the spray-up process, the resin and fibres are sprayed simultaneously on the mould. For this process an air driven chopper is used. This machine chopped the reinforcement into pieces and sprays the chopped pieces together with the resin on the mould. The spray-up system is a high productive process, but the control over required thickness is still in hands of the operator. So for critical application the process is unsuitable, but for high-volume products which are non-critical the spray up method is very suitable. This disadvantage can be overcome when the guns orientation and speed is controlled by a machine. For simple shape this works fine, for difficult shapes a numerical model is needed. See figure 17 for a schematization of the spray-up process. [6]

![Figure 17: Spray-up](30)

4.2.4 Filament winding
Filament winding is a process to produce simple hollow sections. The component is moulded on a rotating mandrel. The fibres are impregnated with resin and are wound around a rotating mandrel. The winding angle can be controlled by changing the relative speed and changing the winding angle. This process is commonly used to produce tanks, pressure vessels, gas bottles etc. See figure 18 for a schematization of this process. Filament winding can be combined with the auto spray process, this is called spray winding. In this method random chopped fibre layers are combined with a wound-on continuous fibre strands. The thickness is built up on a rotating former. The resin is applied by spray gun, with the chopped fibres in the auto spray-up. This method is more cost-effective for low-pressure applications than a totally filament wound laminate. [6]

![Figure 18: Filament winding](30)

4.2.5 Centrifugal casting
Centrifugal casting produces, like filament winding, also hollow section, but with centrifugal casting sections are made with the mould surface on the outside. The resin and reinforcement are placed inside a cylindrical mould which is rotating with a high speed. Due to the accelerating forces, the air is expelling and the laminate is consolidating. The
reinforcement is denser than the resin, therefore the reinforcement tends to move to the outside. This gives a resin rich inner surface. Some advantages are the good fibre content and high production rate. The disadvantage is that only cylindrical sections can be made and the inside is unmolded. [6]

4.3 Closed mould process

4.3.1 Vacuum bag

The vacuum bag is the simplest closed mould process. The resin and reinforcement are applied by hand laminating in an open mould. After this a release film is placed, which is followed by a rubber bag. This bag is clamped at the edges of the mould. The vacuum pump evacuates the space between the bag and the mould. Additional rolling can still be needed to achieve complete consolidation. This method gives the possibility to produce large elements and it is effective to bond sandwich laminate together. A schematisation of the vacuum bag process is given in figure 19. [6]

![Vacuum bag](image)

*Figure 19: Vacuum bag [6]*

4.3.2 Pressure bag

The pressure bag moulding is a similar process as the vacuum bag process. Due to the higher pressure than the atmospheric pressure, higher fibre content and a better consolidation can be achieved. The loads on the mould are much higher, so the mould needs to be more robust than the mould for a vacuum bag. The use of a bag press makes this process quite productive. This process is used for high quality component made with preimpregnated reinforcement (prepreg). The resin has in a prepreg a partially cured state. Under action of the pressure and heat the prepreg will form to the shape of the mould and will be cured. A schematisation of the pressure bag process is given in figure 20. [6]

![Pressure bag](image)

*Figure 20: Pressure bag [6]*

4.3.3 Autoclave

The autoclave process is a combination of the vacuum bag and the pressure bag. In this process a vacuum bag is placed inside a heated and pressurized vessel. Layers of prepregs are placed into the mould to make the full thickness. In this process a vacuum bag is loaded in the autoclave. The laminate is subjected to vacuum, pressure and heat simultaneously. Due to the autoclave, the mould is not subjected to large loads. Therefore the mould can be
made of a light construction. A schematisation of the autoclave process is given in figure 21. [6]

4.3.4 Leaky mould
The leaky mould process consists of a mould where a male and female part is used. These parts are clamped together to form a cavity of the shape of the component. The resin and fibres are placed with the hand laminating process in the female part of the mould. The male part is pressed on the female part. When the curing is complete, the clamps are removed and the mould split. The components are now extracted. This method gives accurate dimensions and a quality finish on both sides. [6]

4.3.5 Cold press
The cold press is similar to the leaky mould, only the mould connected to a hydraulic press. The press is capable to reach a pressure of 2 bar. That makes it possible to distribute the resin and impregnate the reinforcement and purging air at the same time. The reinforcement is placed in as a dry pack on the mould. The resin is mixed and the required quantity is poured into the reinforcement. Now the mould is closed and the pressure is applied. After hardening the mould can be opened and the composite can be removed. The cold press method gives accurate components with a good surface on both sides. A disadvantage is the limited press size, low fibre content and the high investment cost. [6]

4.3.6 Hot press
Execute the cold press process under heated condition, gives an increase of the rate of production. The highest output can be achieved with a minimum temperature of 140 °C. A liquid resin can be used, but mostly a prepgreps or sheet and dough moulding components are used. This method gives a very high production rate with close tolerances. Disadvantages are the limited press size and the high tooling costs. [6]

4.3.7 Resin injection
With the resin injection method the reinforcement is packed and loaded in the mould on the same way as the cold press process. The resin is injected after closure of the mould. The resin is mixed and pumped into the mould with an air-driven dispensing machine. The fill time is between one and ten minutes, depending of the size of the component. Resin injection is limited to use random reinforcement and low fibre content. In comparison with the cold press method, the resin injection can make more complex shapes with a similar production ratio. [6]

4.3.8 Vacuum-assisted resin injection
With the introduction of the vacuum-assisted resin injection, most of the limitations of the resin injection are overcome. The major benefits are the use of large mouldings, higher fibre
content and the possibility to use high strength reinforcements. The reinforcement pack is placed and the mould is closed, after this a seal is placed around the edges of the mould. This introduces a partially vacuum in the mould cavity. After this, the mixed resin is injected by a pump. The upper mould is made of a flexible material, which deforms under the injection pressure. This allows the resin to pass and reform to its proper shape by vacuum. This ensures a high fibre content and good impregnation. Figure 22 gives a schematization of the vacuum assisted resin injection process. [6]

![Figure 22: Vacuum assisted resin injection](image)

**Figure 22: Vacuum assisted resin injection [14]**

### 4.3.9 Injection moulding

The injection moulding process is used to manufacture most thermoplastic components. In this process, the parts, like reinforcement and resin, mixed in a dough. This is placed in the moulding machine hopper and is processed on the same way as unreinforced components. The moulding compound is forced by a screw into the mould. This causes some degradation of the fibres. Only short fibres can be applied and the orientation depends on the flow during filling. So the properties of parts can be variable. See figure 23 for a schematization. [6]

![Figure 23: Injection moulding](image)

**Figure 23: Injection moulding [6]**

### 4.4 Continuous processes

The continuous processes are processes which make a large number of identical elemental in a fast way. In the following sections, three continuous processes will be discussed.

#### 4.4.1 Continuous laminating

The continuous laminating process combines the resin and reinforcement between two layers of release film and carries the laminate over a conveyor through the oven. After leaving the oven, the released film is peeled off and the cured laminate cut to length. The process can make use of a flat sheet or a corrugated profile. The resin impregnation will be done by passing the reinforcement through a bath before the release films are attached or by applying a layer of resin to each release film via a blade and then sandwiching the
reinforcement. This method is highly productive and capital intensive, but the geometry is limited to simple profiles like flat sheets and simple profiles. [6]

4.4.2 Pultrusion

Pultrusion is a process for the production of constant sections of members. The reinforcement is pulled through a bath of resin and pulled through a heated die. The temperature in the die is such that the resin reacts and cures in the die, which forms the final shape. The profile is now ready to cut to length. [6][7]

In the essence, the pultrusion is a simple process. However, to get high quality profiles it requires a lot of knowledge and experience. The shape is determined by the die. But the quantities of resin and reinforcement are critical that the die in filled entirely. The speed of the machine, the die temperature and the resin reactivity are all parameters that need to interact with each other. The pultrusion process achieves a very high fibre contents and mechanical properties. This can be done with the use of continuous yarn, woven cloth or mat reinforcement. With this process it is possible to make open and closed profiles, but the profiles have to be straight. Differences in height are not possible. This method is particularly suitable for the production of a large quantity of beams and columns. [6][7]

![Overview pultrusion](image)

Figure 24: Overview pultrusion

4.4.3 Continuous filament winding

The continuous filament winding is to produce a filament wound pipe continuously. The winding head containing several ‘cheeses’ yarn reinforcement. This yarn is rotating around the mandrel. The pipe will emerge with a constant rate from the curing oven. Additional fibres angels can be achieved by using more than one winding head. Excellent material properties and a high production rate can be obtained. This method is only suitable for circular tubes. [6]

4.5 Comparison manufacturing methods

In table 5 is an overview given of the mentioned manufacturing methods of FRP products. In this table the fibre volume, size range, processing pressure, processing temperature, detail tolerance and relative production cost are given.
<table>
<thead>
<tr>
<th>Type</th>
<th>Fibre volume [%]</th>
<th>Size range [m²]</th>
<th>Procespressure [bar]</th>
<th>Process temp. [°C]</th>
<th>Core mat.</th>
<th>Detail tol. [mm]</th>
<th>Relative equip. costs</th>
<th>Relative prod. cost [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open mould processes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand lamination</td>
<td>13-50</td>
<td>0,25-2000</td>
<td>ambient</td>
<td>ambient</td>
<td>Yes</td>
<td>1,0-5,0</td>
<td>Very low</td>
<td>High</td>
</tr>
<tr>
<td>Automated tape lamination</td>
<td>20-60</td>
<td>0,25-500</td>
<td>ambient</td>
<td>ambient</td>
<td>Yes</td>
<td>0,2-1,0</td>
<td>Low-moderate</td>
<td>Moderate/High</td>
</tr>
<tr>
<td>Saturation</td>
<td>13-50</td>
<td>0,25-2000</td>
<td>ambient</td>
<td>ambient</td>
<td>Yes</td>
<td>1,0-5,0</td>
<td>Low-moderate</td>
<td>Moderate/High</td>
</tr>
<tr>
<td>Spray up</td>
<td>13-21</td>
<td>2,00-100</td>
<td>ambient</td>
<td>ambient</td>
<td>Yes</td>
<td>1,0-3,0</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Auto-spray up</td>
<td>13-21</td>
<td>2,00-100</td>
<td>ambient</td>
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<td>2,0-3,0</td>
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<td>Very Low</td>
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<td>ambient</td>
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<td>1,0-2,0</td>
<td>Moderate-high</td>
<td>Moderate/High</td>
</tr>
<tr>
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<td>0,1-100</td>
<td>ambient</td>
<td>ambient</td>
<td>Yes</td>
<td>2,0-3,0</td>
<td>Moderate-high</td>
<td>Very low</td>
</tr>
<tr>
<td>Centrifugal casting</td>
<td>20-60</td>
<td>0,5-100</td>
<td>40-60</td>
<td>No</td>
<td>1,0-3,0</td>
<td>Moderate-high</td>
<td>Low</td>
<td>Moderate/High</td>
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<td><strong>Closed mould processes</strong></td>
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<td>Vacuum bag</td>
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<td>ambient</td>
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<td>Low</td>
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<td>130-150</td>
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<td>High</td>
<td>Very low</td>
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<td>1-2,0</td>
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<td>Moderate</td>
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<td>750-1500</td>
<td>140</td>
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<td>0,1-0,5</td>
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<td>Very Low</td>
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<td>Very low</td>
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<td>Up to 1m width</td>
<td>varies</td>
<td>130-150</td>
<td>No</td>
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<td>Low</td>
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<td>Up to 2m diam.</td>
<td>ambient</td>
<td>ambient</td>
<td>No</td>
<td>1,0-2,0</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 5: Comparison different manufacturing processes [15][6]
5 Determination of the mechanical properties of a FRP

5.1 Introduction
In the sections before are the applications and manufacturing of a FRP described. In this section equations to estimate the mechanical properties of a FRP will be discussed. Some simple estimation will be given and further more sophisticated methods discussed. In section 5.3 the total built up of a FRP will be discussed with the classic laminate theory. This theory is a method to calculate the properties of a FRP that is built up with different lamellas.

5.1.1 Rule of mixture
The rule of mixture is about the ratio of the fibres and the resin in the material. In the equations the mass of the composite material is called $M_c$, the volume is $V_c$. The masses of the components are called $M_f$ (with the subscript f, which stands for fibres) and $M_r$ (with r stands for resin). In the rule of mixture it is assumed that there are no holes in the material.

The total mass and volume can be written as:
$$M_c = M_f + M_r$$
$$V_c = V_f + V_r$$

The mass and volume are related with each other with the density $\rho$. These densities are:
$$\rho_c = \frac{M_c}{V_c}$$
$$\rho_f = \frac{M_f}{V_f}$$
$$\rho_r = \frac{M_r}{V_r}$$

The volume fractions $v$ are:
$$v_f = \frac{V_f}{V_c}$$
$$v_r = \frac{V_r}{V_c}$$

With these equations, the density of the composite can be written as:
$$\rho_c = \frac{M_f + M_r}{V_c} = \frac{V_f \rho_f + V_r \rho_r}{V_c}$$

This gives when substituting equation (5.3):
$$\rho_c = v_f \rho_f + v_r \rho_r$$

This equation is called the rule of mixture.

By the manufacturing of FRP products the mass off the fibres are known and the quantity resin is weighed. With this the mass fractions $m$ of the components are formulated like:
$$m_f = \frac{M_f}{M_c} = \frac{V_f \rho_f}{V_c \rho_c}; \quad m_r = \frac{M_r}{M_c} = \frac{V_r \rho_r}{V_c \rho_c}; \quad m_f + m_r = 1$$

When the densities are known, the mass fractions can be calculated with:
$$\frac{1}{\rho_c} = \frac{v_f + v_r}{\rho_f + \rho_r} \Rightarrow \rho_c = \left[ \frac{m_f + m_r}{\rho_f + \rho_r} \right]^{-1}$$

Substituting this equation in the equations above gives the volume fractions, written in densities and mass fractions. These fractions are used in several calculations.
\[ r = \frac{\rho}{m \rho + m_i \rho_i}; \quad v = \frac{\rho}{m_i \rho + m \rho_i} \]  

### 5.1.2 Simple determination stiffness model for unidirectional material

The unidirectional material is the simplest shape of a composite. In a unidirectional material are the fibres laying in longitudinal direction. When there is a tension load in the longitudinal direction, the strain on the fibres and resin is equal. This situation can be described with a parallel model. [4]

\[ F = \sigma_f A_f + \sigma_m A_m = F_f + F_m = A_f \sigma_f + A_m \sigma_m \]  

If the load is divided by the total cross-section, the mean longitudinal stress is calculated. The total load can be divided in a fibre part and a resin part.

\[ \sigma_L = \frac{\sigma_f A_f + \sigma_m A_m}{A} = \frac{F_f + F_m}{A} = \frac{A_f \sigma_f + A_m \sigma_m}{A} \]  

So with the rule of mixture the longitudinal stress can be written as:

\[ \sigma_L = \nu_f \sigma_f + \nu_m \sigma_m \]  

With the relation of Hooke’s law, \( \sigma = E \varepsilon \) the strains can be written as:

\[ \varepsilon_L = \frac{\varepsilon_f \varepsilon_f + \varepsilon_m \varepsilon_m}{E_f + E_m} = \frac{\varepsilon_f \sigma_f + \varepsilon_m \sigma_m}{E_f + E_m} \]  

So the longitudinal elastic modulus becomes with substituting (5-11) and (5-12):

\[ E_L = \nu_f E_f + \nu_m E_m \]

The transverse elastic modulus can be calculated on the same way. Figure 26 gives an overview of this method. The fibres and resin are now placed in series. This gives for the transverse elastic modulus the following equation: [4]

\[ \frac{1}{E_T} = \frac{\varepsilon_T}{\sigma_T} = \frac{\nu_f \varepsilon_f + \nu_m \varepsilon_m}{\sigma_f \sigma_m} = \frac{\nu_f \varepsilon_f}{\sigma_f} + \frac{\nu_m \varepsilon_m}{\sigma_m} = \frac{\varepsilon_f}{E_f} + \frac{\varepsilon_m}{E_m} \]  

\[ F = \sigma_f A_f + \sigma_m A_m \]  

\[ \sigma_f \]

Figure 25: parallel model for a unidirectional material, loaded in longitudinal direction [4]

Figure 26: Series model for a unidirectional material, loaded in transverse direction [4]
Equation (5-13) predicts the longitudinal elastic modulus quite well, but equation (5-14) underestimates the transverse elastic modules and is therefore not applicable in practice. In the series model the transverse contraction between the fibres and resin is assumed to be equal. But in reality are the fibres embedded by the resin. This gives a combination of a series and a parallel model. The series model can be improved by taking a part of a series model and a part of a parallel model. A unit cell is taken with a square cross-section. See figure 27 for an overview of this unit cell. With this method the transverse elastic modulus can be written as. The derivation of the transverse elastic modules can be seen on page 11 of [4], the equation becomes:

\[ E_T = \sqrt{\nu_f} \left[ \frac{\nu_f}{E_f} + \frac{1 - \nu_f}{E_r} \right]^{-1} + (1 + \sqrt{\nu_f})E_r \]  

\[ (5-15) \]

Figure 27: Transverse loaded unit cell. [4]

5.1.3 Accurate determination stiffness model for unidirectional material

In the last paragraph simple estimations of the elastic properties are described. In this section different methods will be discussed that determine the properties on a more accurate way.

5.1.3.1 The variation principle of Hashin and Shtrikman

The variation principle of Hashin and Shtrikman compares two different solids, under the same conditions. One of these solids is a heterogenous material and the other homogeneous. The Hashin and Shrikman relations give the most accurate boundaries for the compression modulus \( k^* \), the longitudinal stiffness \( E_L^* \), the poisson ratio \( \nu_{LT}^* \) and the shear modulus \( G_{LT}^* \). The boundaries are given by the following equations: [4]

if \( k_f > k_r \) and \( G_f > G_r \) :

\[ k_r \frac{1}{k_f} \leq k^* \leq k_f + \frac{1 + \nu_f}{k_r} \left( k_f - k_r \right) k_f \leq k^* \leq k_r, \]

\[ (5-16) \]

\[ \nu_f \left( \nu_f - \nu_r \right) \left( \frac{1}{k_f} - \frac{1}{k_r} \right) \leq \nu_{LT}^* \leq \nu_f \left( \nu_f - \nu_r \right) \left( \frac{1}{k_f} - \frac{1}{k_r} \right) \]

\[ (5-17) \]

\[ \nu_f \left( \nu_f - \nu_r \right) \left( \frac{1}{k_f} - \frac{1}{k_r} \right) \leq \nu_{LT}^* \leq \nu_f \left( \nu_f - \nu_r \right) \left( \frac{1}{k_f} - \frac{1}{k_r} \right) \]

\[ (5-18) \]
5.1.3.2 Interpolation equations of Tsai (91-92)

In 1964 Tsai notes that the filament cross-sections are lying partly in strands against each other. So Tsai introduces for his equations a filament contiguity factor ‘C’. Tsai used for his equations two models, in the first model are the filaments cross-sections lying partly in strands against each other. In the second model all the filaments are isolated from each other due to the resin. In reality this lies between these two models and can be set with the factor C. This factor C is an interpolation factor for (C=0) total fibre isolation and complete closed fibres network (C=1).

These results are used as starting points for Halpin and Tsai to make a simplified equation to predict the effective constants of a FRP. Halpin and Tsai succeeded to make one general equation which gives the technical relations between the technical constants. In this equation, $P$ stands for the considered property, without indices it is for the composite. Table 6 gives a scheme with parameters for this equation. This general equation is given by: [4]

$$P = \frac{P_f}{1 - \eta v_f}$$

with \( \eta = \frac{P_f - P_r}{P_f + \zeta P_r} \) \( (5-22) \)

<table>
<thead>
<tr>
<th>( P )</th>
<th>( P_f )</th>
<th>( P_r )</th>
<th>( \zeta )</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_L^* )</td>
<td>( E_{L,f} )</td>
<td>( E_{L,r} )</td>
<td>( \frac{l}{2d} )</td>
<td>( l = ) fibrelength ( d = ) diameter</td>
</tr>
<tr>
<td>( v_{LT}^* )</td>
<td>( v_{LT,f} )</td>
<td>( v_{LT,r} )</td>
<td>( \infty )</td>
<td></td>
</tr>
<tr>
<td>( E_T^* )</td>
<td>( E_{T,f} )</td>
<td>( E_{T,r} )</td>
<td>( \frac{a}{b} )</td>
<td>( a = ) fibresize - ( x_2 ) ( b = ) fibresize - ( x_3 )</td>
</tr>
<tr>
<td>( G_{LT}^* )</td>
<td>( G_{LT,f} )</td>
<td>( G_{LT,r} )</td>
<td>( \left( \frac{a}{b} \right)^{3/2} )</td>
<td></td>
</tr>
<tr>
<td>( G_{LT} )</td>
<td>( G_{LT,f} )</td>
<td>( G_{LT,r} )</td>
<td>( \frac{k}{k_r - 2G_{TT,r}} )</td>
<td>( \zeta = \frac{1}{3 - 4\nu_r} ) for an isotropic resin</td>
</tr>
</tbody>
</table>

Table 6: Scheme parameters Halpin and Tsai equation [4]

Often are the components of a composite assumed to be isotropic, the fibres continuous and with a circular cross section. With this assumptions equation (5-22) can be written in a well know form:

$$\varepsilon_r = v_r \varepsilon_f + v_r \varepsilon_r$$

(5-23)
5.1.3.3 Improvements Halpin Tsai model by Tsai and Hahn

Tsai and Hahn tried to improve the equations of Halpin and Tsai for filaments with a circular cross-section. It is assumed that the resin is isotropic and the fibres are transverse isotropic, which is the case for aramid and carbon fibres. The basic equation is given below. Table 7 gives a scheme with the parameters for this equation which are valid for $G_m << G_{LT,f}$.

$$P = \frac{v_i}{v_j + \eta v_j} P_{f} + \frac{\eta v_j}{v_j + \eta v_j} P_{r}$$  \hspace{1cm} (5-24)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Formula</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_L$</td>
<td>$E_{L,f}$</td>
<td>$E_r$</td>
<td>$l =$ fibre length $d =$ diameter</td>
</tr>
<tr>
<td>$\nu_{LT}$</td>
<td>$\nu_{LT,f}$</td>
<td>$\nu_r$</td>
<td>1</td>
</tr>
<tr>
<td>$\frac{1}{G_{LT}^*}$</td>
<td>$\frac{1}{G_{LT,f}^*}$</td>
<td>$\frac{1}{G_{r}^*}$</td>
<td>$\eta_{LT} = \frac{1}{2} \left( 1 + \frac{G_r}{G_{LT,f}} \right)$</td>
</tr>
<tr>
<td>$\frac{1}{k^*}$</td>
<td>$G_{LT,f}$</td>
<td>$G_{LT,r}$</td>
<td>$\left( \frac{a}{b} \right)^\beta$</td>
</tr>
<tr>
<td>$G_{TT}^*$</td>
<td>$G_{TT,f}$</td>
<td>$G_{TT,r}$</td>
<td>$\frac{k_r}{k_l - 2G_{TT,r}}$</td>
</tr>
</tbody>
</table>

Table 7: Scheme parameters Tsai and Hahn equation [4]

5.1.3.4 Composite cylinder model

In 1964 Hashin and Rosen formulated a consistent model, this model is built of a composite cylinder model. In this model have the fibres a circular cross-section. Each fibre is surrounded by a circular resin. For a cylinder it is assumed that the technical constants are equal to the values of the composite. With this method the lower boundaries of the Hashin Shtrikman for $E_{L}^*, \nu_{LT}^*, G_{LT}^*$ and $k^*$ are obtained.

Christensen en Lo (1979) have derived an equation for the transverse shear modules. There equation is based on the cylinder model, with the assumption that the elastic energy for the heterogeneous material must be equal to the equivalent of the homogeneous material.

5.1.3.5 Empiric equations of Puck

Puck used the rule of mixture to evaluate the values for $E_{L}^*, \nu_{LT}^*, G_{LT}^*$ and $k^*$. With some curve fitting of his experimental data, he made some empiric equations for $E_{L}^*, G_{LT}^*$. These equations can be written in the following general form, the parameters are given in table 8.
\[ P = P_i \frac{1 + \alpha v_i^\beta}{\gamma v_i^\delta} \]  
\[(5-25)\]

<table>
<thead>
<tr>
<th>Glass fibre reinforced polymers (Puck)</th>
<th>[ P = E_i ]</th>
<th>[ P = G_{LT}^* ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ P_f = ]</td>
<td>[ E_f ]</td>
<td>[ G_f ]</td>
</tr>
<tr>
<td>[ \alpha ]</td>
<td>0.85</td>
<td>0.6</td>
</tr>
<tr>
<td>[ \beta ]</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>[ \gamma ]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>[ \delta ]</td>
<td>1.25</td>
<td>1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Glass fibre reinforced polymers (Förster and Knappe)</th>
<th>[ P = E_i ]</th>
<th>[ P = G_{LT}^* ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ P_f = ]</td>
<td>[ E_f ]</td>
<td>[ G_f ]</td>
</tr>
<tr>
<td>[ \alpha ]</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>[ \beta ]</td>
<td>( - )</td>
<td>0.5</td>
</tr>
<tr>
<td>[ \gamma ]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>[ \delta ]</td>
<td>1.45</td>
<td>1.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Glass fibre reinforced polymers (Schneider, Menges and Peulen)</th>
<th>[ P = E_i ]</th>
<th>[ P = G_{LT}^* ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ P_f = ]</td>
<td>[ E_f ]</td>
<td>[ G_f ]</td>
</tr>
<tr>
<td>[ \alpha ]</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>[ \beta ]</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>[ \gamma ]</td>
<td>6</td>
<td>1.25</td>
</tr>
<tr>
<td>[ \delta ]</td>
<td>0.75</td>
<td>1.25</td>
</tr>
</tbody>
</table>

**Table 8: Scheme parameters equations of Puck [4]**

5.1.3.6 *Approximation model of Manera for randomly orientated fibre composites*

The approximation model by Manera is an approximate equation to predict the elastic properties of randomly orientated fibre composites. Manera made a few assumptions and simplified the Puck invariants equations. These assumptions are the fibre aspect ratio, two dimensional random fibre distribution and the randomly orientated fibres are laminated with an infinite layers that are orientated in all directions. These approximation equations are given by: [13]

\[
\bar{E} = v_f \left( \frac{16}{45} E_i + 2E_r \right) + \frac{8}{9} E_r \\
\bar{G} = v_f \left( \frac{2}{15} E_i + \frac{3}{4} E_r \right) + \frac{1}{3} E_r \\
\bar{\nu} = \frac{1}{3}
\]  
\[(5-26)\]

To get adequate precision in the results, the fibre fraction needs to be between the 0.1-0.4 and \( E_r \) within the range of \( 2GPa \leq E_r \leq 4GPa \). [13]

5.1.4 *Comparison equations*

For a comparison of the mentioned equations above, are the fibre fractions calculated and displayed in figure 28. For this comparison E-glass/epoxy is compared with the following properties:

\[ E_f = 70GN/m^2; \nu_f = 0.22; E_r = 3.5GN/m^2; \nu_r = 0.35 \]

For the longitudinal elastic modulus are the boundaries of Hashin & Shtrikman very close to each other. For the other modulus layers these boundaries are further from each other. The
series model of Hill gives even lower boundaries that the lower boundaries of Hashin & Shtrikman. So, ones again the series model is incorrect for a transverse cross-section. The other models are laying closer to the lower boundary of Hashin & Shtrikman. [4]

The equation of Tsai & Hahn for the transverse elastic modulus delivers the same values as the lower boundaries of Hashin & Shtrikman. For the longitudinal transverse shear modulus delivers the lower boundary of Hashin & Shtrikman the same values as the equation of Tsai and Hahn, the equation of Christensen & Lo gives some higher values.
Figure 28: Comparison different models for the technical constants of UD lamella. (fig 4.12 [4])
5.2 Classical laminate theory

5.2.1 Introduction
This section will give a description of the classic laminate theory. The base for this theory is the classic plate theory, which will be first introduced. The laminate theory estimates the properties of a built up laminate with lamellas that can be orientated on a different way.

5.2.2 Classic plate theory
The classic plate theory starts with a thin plate of a constant thickness. The axes are right turning and orthogonal. The xy-axes are chosen in the middle of the plate and the z-axe is perpendicular on the plate. It is assumed that a line perpendicular to the plate will be in deformed state also perpendicular to the plate, which holds that there are no rotations around the z-axe and the stresses in x- or y- axes can be neglected. This is the Kirchhoff-love hypothesis. Figure 29 shows an overview of the axes on the plate. U,v,w are the components of the displacement in x,y and z direction. [4]

\[ \frac{\partial w}{\partial x} \approx 0 \]

\[ \frac{\partial w}{\partial x} \approx 0 \]

\[ u' = -z \sin \beta \approx -z \tan \beta = -z \frac{\partial w^0}{\partial x} \] \hspace{1cm} (5-27)

For the slope of the elastic line counts:

Point B has in the x-direction a displacement of:

So the total displacement from point B in the x-axes becomes:

\[ u = u^0 + u' = u^0 - z \frac{\partial w^0}{\partial x} \] \hspace{1cm} (5-29)
The curvature of the elastic line becomes positive if the convex side of the curve is on the positive \(z\)-axes, but the slope is negative. The curvature of a flat curve is:

\[
\kappa^0_x = \frac{1}{R_x} = \frac{\partial^2 w^0}{\partial x^2} \left(1 + \left(\frac{\partial w^0}{\partial x}\right)^2\right)^{-\frac{3}{2}} \approx -\frac{\partial^2 w^0}{\partial x^2} \tag{5-30}
\]

With \(R_x\) is the radius of curvature of the \(x\)-axes at the point \(A\). These approximations are allowed for small deflections. Partial differentiation from \(u\) to \(x\) gives the strain \(\varepsilon_x\) in the point \(B\):

\[
\varepsilon_x = \frac{\partial u}{\partial x} = \frac{\partial u^0}{\partial x} - \frac{\partial^2 w^0}{\partial x^2} = \varepsilon_x^0 + z\kappa_x^0 \text{ with } \varepsilon_x^0 = \frac{\partial u^0}{\partial x} \tag{5-31}
\]

\(\varepsilon_x^0\) give the strain in the \(x\)-direction in point \(A\) \((x,0,0)\). The strain in the \(y\)-axis will be:

\[
\varepsilon_y = \frac{\partial v}{\partial y} = \frac{\partial v^0}{\partial y} - \frac{\partial^2 w^0}{\partial y^2} = \varepsilon_y^0 + z\kappa_y^0 \text{ with } \varepsilon_y^0 = \frac{\partial v^0}{\partial y} \text{ and } \kappa_y^0 \approx -\frac{\partial^2 w^0}{\partial y^2} \tag{5-32}
\]

For the shear strain between the \(x\)- and \(y\)-direction in point \((x,y,z)\) counts:

\[
\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = \frac{\partial}{\partial y} \left(u^0 - z \frac{\partial w^0}{\partial x}\right) + \frac{\partial}{\partial x} \left(v^0 - z \frac{\partial w^0}{\partial y}\right) = \frac{\partial u^0}{\partial y} + \frac{\partial v^0}{\partial x} - 2z \frac{\partial^2 w^0}{\partial x \partial y} = \gamma_{xy}^0 + z\kappa_{xy}^0 \tag{5-33}
\]

With: \(\gamma_{xy}^0 = \frac{\partial u^0}{\partial y} + \frac{\partial v^0}{\partial x}\) and \(\kappa_{xy}^0 = -2\frac{\partial^2 w^0}{\partial x \partial y}\)

Curvature \(\kappa_{xy}^0\) is the twisting curvature in the \(xy\)-plane.

The deformations of a plane parallel to the middle plane can be taken up by the strain state vector, which consist of the strain state vector and the curvature vector.

This can be notated as:

\[
\{\varepsilon\} = \{\varepsilon^0\} + z\{\kappa^0\} \tag{5-34}
\]

With:

\[
\{\varepsilon\} = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}, \quad \{\varepsilon^0\} = \begin{bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{bmatrix}, \quad \{\kappa^0\} = \begin{bmatrix} \kappa_x^0 \\ \kappa_y^0 \\ \kappa_{xy}^0 \end{bmatrix}, \quad \{\kappa^0\} = \begin{bmatrix} \frac{\partial^2 w^0}{\partial x^2} \\ -\frac{\partial^2 w^0}{\partial y^2} \\ -2\frac{\partial^2 w^0}{\partial x \partial y} \end{bmatrix} \tag{5-35}
\]

For a rectangle part of a plate, the sides are parallel to the coordinate system. Cause of the plane stress, in these surface only the normal stresses \(\sigma_x, \sigma_y\) and the shear stress \(\tau_{xy}\) are...
working. When these stresses are integrated over the height of the plate, the forces $N_x$, $N_y$, and $N_{xy}$ are obtained. [4]

$$
\begin{align}
N_x &= \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x dz; \\
N_y &= \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_y dz; \\
N_{xy} &= \int_{-\frac{h}{2}}^{\frac{h}{2}} \tau_{xy} dz \tag{5-36}
\end{align}
$$

These forces have the same direction as the stresses. These force resultants are applied in the middle plane. This gives some bending moments ($M_x$ and $M_y$), twisting moment ($M_{xy}$).

The force and moments resultants are schematized in a plane element in figure 30. These moments are: [4]

$$
\begin{align}
M_x &= \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x z dz; \\
M_y &= \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_y z dz; \\
M_{xy} &= \int_{-\frac{h}{2}}^{\frac{h}{2}} \tau_{xy} z dz \tag{5-37}
\end{align}
$$

![Figure 30: Force and moments resultants (fig 3.13 [5])](image)

The resultants of the forces can be written as the following vectors:

$$
\{N\} = \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{h} \sigma_x \\ \frac{1}{h} \sigma_y \\ \frac{1}{h} \tau_{xy} \end{bmatrix} dz = \begin{bmatrix} \sigma \end{bmatrix} dz
$$

$$
\{M\} = \begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{h} \sigma_x \\ \frac{1}{h} \sigma_y \\ \frac{1}{h} \tau_{xy} \end{bmatrix} zdz = \begin{bmatrix} \sigma \end{bmatrix} zdz \tag{5-38}
$$

With Hooke’s law the plain stresses can be written as:

$$
\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{11} & 0 \\ Q_{66} & Q_{66} & 0 \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}
$$

with $Q_{11} = \frac{E}{1-\mu^2}$; $Q_{12} = \mu Q_{11}$; $Q_{66} = G = \frac{E}{2(1+\mu)} \tag{5-39}$

Now this equation can be substituted in the resultants of forces, which gives:
\[ \{ N \} = \left[ Q \right] \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \{ \varepsilon \} dz = \left[ Q \right] \left( \left\{ \varepsilon^0 \right\} + \left\{ \kappa^0 \right\} z \right) dz = h[Q]\left\{ \varepsilon^0 \right\}; \]
\[ \{ M \} = \left[ Q \right] \int_{-\frac{1}{2}h}^{\frac{1}{2}h} \{ \varepsilon \} z dz = \left[ Q \right] \left( \left\{ \varepsilon^0 \right\} z + \left\{ \kappa^0 \right\} z^2 \right) dz = \frac{1}{12}h^3 [Q] \left\{ \kappa^0 \right\} \]

(5-40)

5.2.3 Laminate theory

A laminate consist of a number of layers of a constant thickness, called lamellas. It is assumed that the laminate is under plane stress and it is assumed that the laminate is glued, so that there is no shift between the lamellas and satisfies the Kirchhoff-love hypotheses. Than the classic plate theory can be applied on the lamellas, with this the laminate theory would be built. [4]

The lamellas are numbered in stacked sequence, starting from the underside of the laminate. These numbers is indicated with \( k \). For this laminate a right-handed orthogonal xyz coordinate system associated. The xy-axes coincide with the middle plane. Every lamella \( k \) has its own coordinate system. So Hooke’s law for every lamella \( k \) will be: [4]

\[ \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{bmatrix}_k = \begin{bmatrix} Q_{11} & Q_{12} & Q_{16} \\ Q_{21} & Q_{22} & Q_{26} \\ Q_{61} & Q_{62} & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_6 \end{bmatrix}_k \text{, or shorter: } \left\{ \sigma \right\}_k = [Q] \left\{ \varepsilon \right\}_k \]

(5-41)

Every lamella will be coupled with a \( (x_i', y_i', z_i') \)-axes, which is parallel to the xyz-axes. \( (x_i', y_i', z_i') \)-plane is equal to the \( (x_i, y_i, z_i) \)-plane with a rotation of \( \theta_k \), with the angle \( \theta_k \) counter clockwise is positive. To describe the built up of the laminate, the following notation can be used. When the lamellas are identical only the orientation angels has to be noted. For example: \([0/0/30/-30/30/90/90/30/-30/0/0]\). With lamellas with the same angle can be noted with a indices like: \([0_1/30/-30/90/, -30/30/0_0]\] and when the laminate is symmetric this can be simplified to: \([0_1/30/0_0/90]_s\). [4]

Hooke’s law for the transformed lamella \( k \) is given by:

\[ \begin{bmatrix} \sigma'_1 \\ \sigma'_2 \\ \sigma'_6 \end{bmatrix}_k = \begin{bmatrix} Q'_{11} & Q'_{12} & Q'_{16} \\ Q'_{21} & Q'_{22} & Q'_{26} \\ Q'_{61} & Q'_{62} & Q'_{66} \end{bmatrix} \begin{bmatrix} \varepsilon'_1 \\ \varepsilon'_2 \\ \varepsilon'_6 \end{bmatrix}_k \text{, or shorter: } \left\{ \sigma' \right\}_k = [Q'] \left\{ \varepsilon' \right\}_k \]

(5-42)

The stiffness resin is transformed over an angle - \( \theta_k \). The result of the transformed stiffness resin will be:

\[ Q'_{11} = Q_{11} \cos^4 \theta + Q_{22} \sin^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + 4Q_{16} \sin \theta \cos \theta - 4Q_{26} \sin \theta \cos \theta \]
\[ Q'_{22} = Q_{11} \sin^4 \theta + Q_{22} \cos^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + 4Q_{16} \sin \theta \cos \theta + 4Q_{26} \sin \theta \cos \theta \]
\[ Q'_{12} = (Q_{11} + Q_{22} - 4Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{12} (\sin^4 \theta + \cos^4 \theta) + 2(Q_{16} - Q_{26}) \sin \theta \cos \theta (\sin^2 \theta - \cos^2 \theta) \]

(5-43)
\[ Q'_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\cos^2\theta + Q_{66}(\sin^4\theta + \cos^4\theta) + 2(Q_{16} - Q_{26})\sin\theta\cos\theta(\sin^2\theta - \cos^2\theta) \]

\[ Q'_{16} = (Q_{11} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta - (Q_{22} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta + Q_{16}\cos^2\theta(3\sin^2\theta - \cos^2\theta) + Q_{26}\sin^2\theta(\sin^2\theta - 3\cos^2\theta) \]

\[ Q'_{26} = (Q_{11} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta - (Q_{22} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta + Q_{16}\sin^2\theta(\sin^2\theta - 3\cos^2\theta) + Q_{26}\cos^2\theta(3\sin^2\theta - \cos^2\theta) \]

Most of the lamellae are orthotropic, so when the xy-axes are chosen in the main directions of the lamella, than the following holds:

\[ (Q_{16})_k = (Q_{26})_k = 0. \]

Now Hooke’s law can be simplified to:

\[ [Q] = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \]

with

\[ Q_{11} = \frac{E_i}{1-\nu_{12}\nu_{21}}; \quad Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}}; \quad Q_{12} = \frac{\nu_{21}E_i}{1-\nu_{12}\nu_{21}}; \quad Q_{66} = \frac{1}{G_{12}} \]

With this equation (5-43) can be written as:

\[ Q'_{11} = Q_{11}\cos^4\theta + Q_{22}\sin^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta \]

\[ Q'_{22} = Q_{11}\sin^4\theta + Q_{22}\cos^4\theta + 2(Q_{12} + 2Q_{66})\sin^2\theta\cos^2\theta \]

\[ Q'_{12} = (Q_{11} + Q_{22} - 4Q_{66})\sin^2\theta\cos^2\theta + Q_{12}(\sin^4\theta + \cos^4\theta) \]

\[ Q'_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})\sin^2\theta\cos^2\theta + 2Q_{66}(\sin^4\theta + \cos^4\theta) \]

\[ Q'_{16} = (Q_{11} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta - (Q_{22} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta \]

\[ Q'_{26} = (Q_{11} - Q_{12} - 2Q_{66})\sin^3\theta\cos\theta - (Q_{22} - Q_{12} - 2Q_{66})\sin\theta\cos^3\theta \]

The z-coordinates of lamella \( k \) is given by \( z_k \) and \( z_{k+1} \) with \( z_{k+1} < z_k \). The thickness of a laminate is called \( h \). Than the boundaries of a laminate are \( z_0 = -1/2h \) for the beneath surface and \( z_r = 1/2h \) for the upper surface, see figure 31 for an overview. [4]

![Figure 31: Definition of the ply coordinates (fig. 3.2 [5])](image-url)
The deflections on a distance $z$ from the middle plan are formulated for lamella $k$:
$$\{\varepsilon\}'_k = \{\varepsilon_0\} + z[\kappa^0]; \quad z_{k-1} \leq z \leq z_k$$
(5-46)

The associated stresses for lamella $k$ are formulated with:
$$\{\sigma\}'_k = [Q]'_k \{\varepsilon_0\} + z[Q]'_k [\kappa^0]; \quad z_{k-1} \leq z \leq z_k$$
(5-47)

If these equations are filled in equation (5-38), with the assumptions that the stress develops linear in a lamella, but can have a bound between the different lamellas, the following result is obtained:
$$\{N\} = \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \sum_{k=1}^{n} \int_{z_{k-1}}^{z_k} \begin{bmatrix} \sigma^1_x \\ \sigma^1_y \\ \sigma^1_{xy} \end{bmatrix} \, dz = \sum_{k=1}^{n} \int_{z_{k-1}}^{z_k} \{\sigma^1\}'_k \, dz$$
(5-48)

With equation (5-47), equation (5-48) becomes:
$$\{N\} = \sum_{k=1}^{n} [Q]'_k (z_k - z_{k-1}) \{\varepsilon_0\} + \left[ \frac{1}{2} \sum_{k=1}^{n} [Q]'_k (z_k^2 - z_{k-1}^2) \right] [\kappa^0]$$
$$\{M\} = \left[ \frac{1}{2} \sum_{k=1}^{n} [Q]'_k (z_k^2 - z_{k-1}^2) \right] \{\varepsilon_0\} + \left[ \frac{1}{3} \sum_{k=1}^{n} [Q]'_k (z_k^3 - z_{k-1}^3) \right] [\kappa^0]$$
(5-49)

Now the components of the in plane stiffness are defined:
$$A_{ij} = \sum_{k=1}^{n} (Q)'_k (z_k - z_{k-1}); \quad i, j = 1, 2, 6;$$
(5-50)

The coupling stiffness constants are defined by:
$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} (Q)'_k (z_k^2 - z_{k-1}^2); \quad i, j = 1, 2, 6;$$
(5-51)

The bending stiffness constants by:
$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} (Q)'_k (z_k^3 - z_{k-1}^3); \quad i, j = 1, 2, 6;$$
(5-52)

Now equation (5-49) can be written in resin for $m$:
$$\begin{bmatrix} \{N\} \\ \{M\} \end{bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{bmatrix} \{\varepsilon_0\} \\ [\kappa^0] \end{bmatrix}$$
(5-53)

5.2.3.1 Stiffness analysis of a laminate

The properties of the orthotropic lamellas of the built up laminate are assumed to be known. To calculate the deformation by a given load equation (5-53) needs to be inverted. The result of this inversion is given by [4]
$$\begin{bmatrix} \{\varepsilon_0\} \\ [\kappa^0] \end{bmatrix} = \begin{bmatrix} [a] & [b] \\ [b]^T & [d] \end{bmatrix} \begin{bmatrix} \{N\} \\ \{M\} \end{bmatrix}$$
(5-54)
In equation (5-54) $[a]$ is called the component of in plane compliances $[b]$ is called the coupling compliances and $[d]$ is called the bending compliances. Sub matrices $[a]$ and $[d]$ are symmetric, the coupling resin commonly not. [4]

These matrices are given by:

$$[a] = ([A] - [B][D]^{-1}[B])^{-1}$$

$$[b] = ([B] - [D][B]^{-1}[A])^{-1} = -[a]D[B]^{-1}$$

$$[d] = ([D] - [B][A]^{-1}[B])^{-1}$$

5.2.3.2 Influence of a built up laminate

When a composite is randomly built up, there occurs coupling between the normal forces and the moments. This coupling is described in formulas above with the resin $[B]$. Coupling does not occur in isotropic plates. Next to the coupling effect of resin $[B]$, there are some effects that also not present in an isotropic plate. This is caused when the properties $A_{16}, A_{26}, D_{16}$ and $D_{26}$ are unequal to zero. Figure 32 gives a schematization of these coupling effects for different situations. [4]

![Diagram of laminate with coupling effects](image)

*Figure 32: Possible coupling effects for a loaded laminate, with the reference to the laminate compliances in the resin. [4]*

These coupling effects make the behaviour of a laminate complicated. For a designer it makes life easier when the coupling resin is equal to zero. This can be ensured to make a laminate with a symmetric built up. The compliances matrixes from (5-55) are than given by:

$$[B] = 0 \quad \rightarrow \quad [a] = [A]^{-1}; \quad [b] = 0; \quad [d] = [D]^{-1}$$

(5-56)
6 Codes and guidelines

6.1 Introduction

There is a large variety of fibre types, resins or combination of fibres with resins. There are also a lot of application possibilities of composite materials. Until now there are still no universal codes and easy design procedures for FRP. In contrary to the traditional materials, where the properties doesn’t differ much, the choice of FRP introduces a parameter study. The first codes where mainly introduced in Canada and Japan. These codes are for specific applications, mainly for strengthened or FRP reinforced concrete. Other codes are still in developing. For specific products like profiles are design handbooks of the manufacturer available, like Fiberline, Creative Pultrusion, etc. To get FRP its own place in Civil engineering market, there needs to be a manufacturer independent application codes. The problems which are now available, like the wide variety of materials can be overcome to divide a code in classification categories. [1]

The codes that are applicable in the Netherlands are:
- Eurocomp - Design code and handbook 1996
- CUR recommendation 96 - Vezel versterkte kunststoffen in civiele draagconstructies 2003
- Rapport 2003-6 - background recommendation CUR 96

In the end of 2012 there will be a new release of the CUR recommendation.

6.2 Eurocomp - Design and handbook

The Eurocomp is produced for the construction industry. The code would give the designer the opportunity to use a composite for structural applications. The design code is intended to be familiar for engineers, who worked with the conventional materials like steel, concrete and timber. The scope of the Eurocomp code is limited by FRP materials made of glass fibres components, but should also be applicable for other fibres. [7]

The Euromp book consists of three parts:
1. Eurocomp Design Code
2. Eurocomp Handbook
3. Test Reports

The Eurocomp design code is applicable for the structural design of buildings and civil engineering. The Eurocomp design code is only concerned for the requirements for resistance, serviceability and durability. Requirements like thermal or sound insulation are not considered. [7]

The Eurocomp handbook is intended to provide additional information to supplement the Eurocomp Design Code. The handbook tries to make it easy for the designer to understand the decisions that has to be made. In particular it is made to cover the areas where the designer has insufficient experience. [7]

Part 3: Test Reports, gives an overview of 5 tests that are done on FRP panels. The tests included panel of bridges and several types of connections. [7]
6.3 CUR Recommendation 96 with background report CUR 2003-6

The CUR recommendation 96 is specific written for the design of civil constructions made of glass-fibre composites. The recommendation is written to stimulate the use of glass fibre composites for a construction material. The CUR report is also as the Eurocomp book divided in two parts. The recommendation can be used as the code and the background reportage for additional and background information.

6.3.1 CUR Recommendation 96

The CUR 96 recommendation is focused on the material properties, calculation of the strength and stiffness properties. Next to these also the materials factors are described. The CUR 96 is only applicable for glass FRP structures. The recommendation does not cover the design of connections in FRP structures.

6.3.2 CUR 2003-6 background report

The background report of the CUR recommendation gives the user of the CUR96 detailed background information. The report focuses mainly on material, material properties and the material factors that are used in the recommendation. It also describes how to deal with fatigue loads.

6.4 Criterions FRP according CUR recommendation 96

In this section the criterions of the CUR recommendation 96 are given. The CUR recommendation is the most important code in the Netherlands and is based on the Eurocomp.

6.4.1 Scope

The CUR96 is applicable for limited cases. The recommendation is only written for the use of glass fibres. The minimum glass fibre percentage needs to be 20%. A laminate has fibres in different directions, therefore a minimum amount of fibres is set for all the directions. So there will be resistance for creep in all the directions. The minimum glass fibre volume needs to be in the directions 0°, 45°, 90° and -45° at least 15%. This can give in the main direction a maximum of 55% of the fibres.

There are some differences with these limitations in the new recommendation that is still in development. The new recommendation is not only for glass fibres applicable, also for carbon and aramid. The minimum fibres percentage is lowered to 15% and the minimum fibres in the directions is lowered from 15% to 12,5 %

6.4.2 Determination materials properties of lamellas according CUR recommendation 96

6.4.2.1 UD-lamella

The material properties of a UD-lamella can be determined with the semi-empiric equations of Halpin and Tsai. These equations are valid for a fibre volume content $V_f$ between the 40% to 70%.

$$E_1 = E_R + (E_F - E_R) \cdot V_f$$  \hspace{1cm} (6-1)

$$E_2 = E_R \cdot \left(\frac{1 + \zeta \cdot \eta \cdot V_f}{1 - \eta \cdot V_f}\right)$$  \hspace{1cm} (6-2)

with: $\eta = \frac{E_F / E_R - 1}{E_F / E_R + \zeta}$ and $\zeta = 2$
\[ G_{12} = G_R \left( \frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot V_f} \right) \quad (6.3) \]

with: \( \eta = \frac{G_F / G_R - 1}{G_F / G_R + \xi} \) and \( \xi = 1 \)

\[ \nu_{12} = \nu_R - (\nu_R - \nu_F) V_f \quad (6.4) \]

6.4.2.2 Weave-lamella

With the same equations of Halpin and Tsai are also the mean stiffness properties estimated of the balanced weave lamellas. These equations are valid for a fibre volume percentage of \( V_f \) of 25% to 55%: [20]

\[ E_1 = \frac{1}{2} \left( E_F + (E_F - E_R) \cdot V_f \right) + E_R \left( \frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot V_f} \right) \quad (6.5) \]

with: \( \eta = \frac{E_F / E_R - 1}{E_F / E_R + \xi} \) and \( \xi = 2 \)

\[ E_2 = \frac{1}{2} \left( E_F + (E_F - E_R) \cdot V_f \right) + E_R \left( \frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot V_f} \right) \quad (6.6) \]

with: \( \eta = \frac{E_F / E_R - 1}{E_F / E_R + \xi} \) and \( \xi = 2 \)

\[ G_{12} = G_R \left( \frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot V_f} \right) \quad (6.7) \]

with: \( \eta = \frac{G_F / G_R - 1}{G_F / G_R + \xi} \) and \( \xi = 1 \)

\[ \nu_{12} = \nu_R - (\nu_R - \nu_F) V_f \quad (6.8) \]

with: \( \eta = \frac{E_F / E_R - 1}{E_F / E_R + \xi} \) and \( \xi = 2 \)

6.4.2.3 Mat-lamella

For mat lamellas the material properties can be calculated with the equations of Manera for fibre volume contents of 10% to 30%. With this method first the properties \( E_1, E_2, G_{12} \) and \( \nu_{12} \) would be determined with the equations of Halpin-Tsai for UD-lamellas; the properties are called here \( E_{1UD}, E_{2UD}, G_{12UD} \) and \( \nu_{12UD} \). With these values some parameters are calculated: [20]

\[ C_{11} = \frac{E_{1UD}^2}{1 - \nu_{12UD}^2 \cdot E_{2UD} / E_{1UD}} \quad (6.9) \]

\[ C_{12} = \frac{E_{2UD}}{1 - \nu_{12UD}^2 \cdot E_{2UD} / E_{1UD}} \quad (6.10) \]

\[ C_{12} = \frac{\nu_{12UD} \cdot E_{2UD}}{1 - \nu_{12UD}^2 \cdot E_{2UD} / E_{1UD}} \quad (6.11) \]

\[ C_{66} = G_{12UD} \quad (6.12) \]
\[ U_1 = \frac{3C_{11} + 3C_{22} + 2C_{12} + 4C_{66}}{8} \]  
\[ U_4 = \frac{C_{11} + C_{22} + 6C_{12} - 4C_{66}}{8} \]  

With this parameters the material properties \( E_1, E_2, G_{12} \) and \( \nu_{12} \) can be calculated with:

\[ E_{11} = \frac{(U_1 + U_4) \cdot (U_1 - U_4)}{U_1} \]  
\[ E_{11} = \frac{(U_1 + U_4) \cdot (U_1 - U_4)}{U_1} \]  
\[ G_{12} = \frac{U_1 - U_4}{2} \]  
\[ \nu_{12} = \frac{U_4}{U_1} \]  

6.4.3 **Strength of laminates**

The Cur report uses a simple strain criterion to simplify complex strength calculations by. According to this criterion must the strain be smaller than 1.2% in every considered direction. An exception can be made for the interlaminar shear stress. [20]

6.4.3.1 **First ply failure - strain criterion**

The base of the first ply failure strain criterion assumes that failure is reached when the first lamella in a laminate has reached the ultimate strain. The strain criterion is one of the simplest criterions to use. Every separate strain must satisfy this criterion. This criterion can be written as:

\[ \frac{\varepsilon_{i,j,s}}{\varepsilon_{i,j,R}} \leq \frac{1}{\gamma_f \cdot \gamma_m \cdot \gamma_c} \]  

with:

\( i = \) direction 1, 2, 12

\( j = \) tension direction, compression direction or shear direction

6.4.3.2 **First ply failure - stress criterion**

The first ply failure can also be applied as a stress criterion. For each lamella needs the stress to be considered. This criterion can be written as: [20]

\[ \frac{\sigma_{i,j,s}}{\sigma_{i,j,R}} \leq \frac{1}{\gamma_f \cdot \gamma_m \cdot \gamma_c} \]  

with:

\( i = \) direction 1, 2, 12

\( j = \) tension direction, compression direction or shear direction

Stresses can be considered only on laminate level, if the laminate is uniform. The laminate is uniform when all the lamellas are equal and orientated in the same direction. When the laminate is built of different elements, the strain can be the same, but the stresses not. Normally the stress is different over the height of the laminate. So the stress criterion needs to be considered for every lamella.
6.4.3.3 Last ply failure

The last ply failure can be used to determine the ultimate failure of the laminate, in contrary to the first ply model. The laminate will collapse when the last lamella has failed. For the calculation of residual strength with the last ply failure must earlier failed lamellas not taken into account. [20]

6.4.3.4 Combined stress criterion

The combined stress criterion takes the coupling effect in different direction. This has the same shape as the criterion of Von Mises for isotropic materials. Tsai and Azzi have expanded this criterion to use it for orthotropic materials, but is not always applicable. [20]

The combined stress criterion of Tsai-Wu is more comprehensive. The criterion for plane stress is given by:

\[
\frac{1}{\sigma_{1,R}} + \frac{1}{\sigma_{1,c,R}} \sigma_{1,j,S} + \left( \frac{1}{\sigma_{2,R}} + \frac{1}{\sigma_{2,c,R}} \right) \sigma_{2,S} - \frac{\sigma_{1,j,S}^2}{\sigma_{1,R} \sigma_{1,c,R}} - \frac{\sigma_{2,j,S}^2}{\sigma_{2,R} \sigma_{2,c,R}}
\]

\[
+ \frac{\tau_{12,S}^2}{\tau_{12,R}^2} \leq \left( \frac{1}{\gamma_f \cdot \gamma_m \cdot \gamma_c} \right)^2
\]  

(6-21)

For a calculation are the strength properties of the laminate needed. This can be tested or calculated with the earlier considered equations. The criterion needs to meet the criterions for each layer lamella in a laminate. It is assumed that the strain of the resin is larger than the strain of the fibres. And the resin cannot carry any load when the fibres are broken.

6.4.4 Fatigue

6.4.4.1 Introduction

A structure component can fail at once due to a high load. The same structure can fail due to a lower load which varies over time. This phenomenon, when the material properties degrade due to a load that fluctuates over time is called fatigue. [11]

The fatigue behaviour can be described with S-N lines, Goodman diagrams, Rainflow counting’s and Minor summations. This is the same method as for the conventional materials like concrete and steel, but the specific parameters are different. For steel there is a fatigue boundary, for concreter there is a quasi-fatigue boundary. For FRP there is no fatigue boundary, but the slope of the S-N lines is much favourable. [20]

For a composite material there can be distinguished three stages for the stiffness reduction. Figure 33 gives a schematization of this process.

- Stage I gives the stiffness reduction in the first part of the lifetime. This stiffness reduction will lie between the 10-20%.
- Stage II gives a reduction of the stiffness which is quite linear, with respect to the number of cycles.
- Stage III is the final region, in this stage reduces the stiffness abrupt and fracture occurs.

It is clear that a structure never may reach stage III. With a fatigue analysis and the use of material factors a structure needs to be designed where this is prevented. [11][20]
6.4.4.2 Fatigue behaviour for a load with a constant amplitude

When a load has a constant amplitude, the mean stress level doesn’t change. The mean stress value can be characterized by an R-value and is defined by:

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]

With :
- \( \sigma_{\text{min}} \) = Minimum stress during change of load
- \( \sigma_{\text{max}} \) = Maximum stress during change of load

For the description of the fatigue behaviour of a FRP, the S-N curve can be used for a completely reversed tension compression cycling loading (R=-1). The S-N curve describes the amplitude between the stresses and the number of fluctuation to fracture. [20]

A linear constant fatigue life (CFL) diagram for a material that is symmetric around the axis is given in figure 34. This symmetric Goodman diagram gives the relation between the stress amplitude and the mean stress level. [20]
6.4.4.3 Fatigue behaviour for a load with a variable amplitude

In the last section the fatigue behaviour is described for a constant load. The most loads on a structure are not constant, so in this section the behaviour is described for a load with a variable amplitude load. Mostly the damage rule of Minor is used. This is a linear rule which divided the loads in numbers of alternates with the same amplitude. These numbers are divided by the mean R-value. The Minor summation is given below: [20]

\[
D = \sum_{i} \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + ... + \frac{n_M}{N_M} \leq 1
\]

With:
- \( n_i \) = number of alternates for a certain load and R-value
- \( N_i \) = number of alternates which causes fracture for a certain load and R-value

For each component the number of alternates to fracture needs to be determined with the Goodman diagram or with the S-N curve for an R-value. A component is considered to be failed when the value \( D \) is larger than 1. [20]

There are different ways to describe the alternates over a time. The most used algorithms are the Rainflow counting and the Range-pair-range counting. A schematization of the Rainflow counting method is given in figure 35. The Rainflow method is like water that passes different roofs to beneath. The time series are divided in half and whole alternates. De physic background comes from the closed hysteric curves in a stress or strain series that is summed up. [20]
The Range-pair-range method gives the same results as the Rainflow method, but is easier to implement in software. This algorithm is made of 4 consecutive extremes. When the middles two extremes are lying between the most outside extremes, this is called as a cycle and deleted from the time series. Now there are again 4 extremes considered and intermediate extremes are deleted. This process can be repeated, until there are no extremes left to delete. [20]

When the R-value has no influence on the fatigue behaviour, only one range needs to be saved. This gives a series numbers which gives for every range the number of cycles. The fatigue behaviour for a FRP is dependant of the R-value, so for every cycles are the mean stress, the R-value of the minimum or maximum cycles needed. This data is counted in a 2D-resin; a resin element gives the number of cycles of a stress/amplitude combination that occur in a time series. [20]

6.4.5 Conversion factors due to creep

Like mentioned before, creep effects are dependant of several factors, like load, fibre direction in relation with the load, type of fibres, fibre volume percentage, manufacturing method etc. Due to the requirement that every direction must contain minimal 15% of the fibres, it is prevented that the load only has to be taken by the resin. The CUR recommendation is a distinction made between the different forms of fibres. Unidirectional composite have less influence than weave lamellas and these have less influence than mat lamellas. This time dependant factor is taken into account with the empiric equation of Holmes and Just. [20]

The conversion factor for creep effects is dependable of the duration of the load and the type of fibres in the direction of the load. This conversion factor is calculated with the following equation: [20]

$$\gamma_{ck} = t^n$$  \hspace{1cm} (6-24)

With:

$\gamma_{ck}$ = duration of the load in hours
For laminates with UD, weave lamellas with different fibre orientations, or eventually combined with mat lamellas, the following approach is given:

1. Determine which UD- or weave lamellas are lying with their fibres in the direction of the long term load.
2. Calculate the long term increment of the strain in the UD- or weave lamellas which have their fibres in the direction of the load on the following way:
   - Calculate first the strain under a long term load in the direction of the long term load of the original laminate.
   - Omit the UD- or weave lamellas which have their fibres in other directions than the load, or give these a stiffness which is equal to zero. Now calculate the strain under the long term load again.
   - Calculate the factor the increment of the strain by calculating the quotient of both strains.
3. Multiply the factor with the creep factor which is calculated with equation (6-24). This gives the final creep factor. [20]

An alternative for this method is Finley’s theory. With this theory the parameters are determined with tests. [22]
7 Structural design

7.1 Introduction
The design of composites is an interactive process between the material design, the structural design and the manufacturing techniques. This chapter will discuss the considerations that have to be taken during the design of a structure.

7.2 Management of a design process

7.2.1 Design considerations
The design process of a FRP consists of a lot of choices. A composite material is made of at least two materials, the fibres and the resin. They are mixed to work together and make use of both characteristics and thereby providing additional qualities to the material.

Some differences have to be taken into account during the design are:
- Composites are mostly orthotropic and inhomogeneous
- Stiffness is governing, instead of strength
- The manufacturing process has a lot of influence on the material properties
- Resins are combustible

7.2.2 Designing the laminate
Composites have some different properties than the most applied materials like steel and concrete. These materials have isotropic properties and are homogeneous. FRP products occur in different forms. Most are orthotropic, such as an unidirectional reinforced polymer, where the material properties in fibre direction are different than the properties at 90 °C of the fibres. Planar-isotropic, when the fibres consist of chopped strand glass fibres. And also isotropic when the fibres are divided in short fibres, randomly places over the polymer by injection moulding. In all cases the composite is inhomogeneous. Cause of the anisotropy properties of composite materials, it is possible to develop a high effective construction, with more fibres at the places where higher capacity are needed. [6]

7.2.3 Designing of joints and assemblies
An advantage of composites is that the material is chemically joint during manufacturing. For small structures is this ideal, because there is no problem with transporting the structure to the final location. With larger structures this is not always possible, cause of the size of the mould or transporting possibilities. So the structure can be made of a number of components and combined later. Possibilities are to combine the components with mechanical joints or bonded joints. [6]

7.2.4 Designing for costs
The costs of a product are not only dependant of the costs of the base materials. Some parts that reduce the design costs are to reduce the handling costs. The designer has to think about the manufacturability, so for example a mould that can be used for several parts. Increase the environmental resistance, so that the maintenance costs are low, etc. Composites have unique properties and can be stronger for parts where extra strength or stiffness is needed. When several parts with the same dimensions and properties can be made, this can give some repetition. [6]
7.3 Structural component design techniques

7.3.1 Preliminary design analysis

The design of a composite is an iterative process. This process consists the choice of a fibre and matrix material and laminate structure. The properties of the laminate can be determined with measurements or calculated with the classical laminate theory (CLT). These data is needed as input for the structural analysis. This process becomes iterative when the laminated structure is changed to improve the structural performance. The design freedom is one of the successes of FRP materials; it is also the main reason for the increased complexity in design analysis with these materials. [6]

Calculate of the structure can resist the load is quite simple for small structures. When the structure becomes larger a Finite Element Analysis (FEA) can be made. Most FEA programs are not specific for composites, but have the choice to use orthotropic materials with specified mechanical properties. [6]

These mechanical properties can be calculated with the earlier mentioned theories. Figure 36 gives the flow chart of calculating the laminate stiffness. The first step is to choose a lamina. The composite has to meet the requirements of the CUR recommendation 96. So it is convenient to determine the mechanical properties of the lamina with the equations from the CUR recommendation 96. These equations are for a unidirectional and a weave lamella the semi-empiric equations of Halpin and Tsai. For mat lamella the equations of Manera can be used. After this a choice for the laminate has to be made for the thickness, number, rotating angle and the stacking order of the lamellas. [20][21]

The second step is to determine the stiffness properties $Q_{ij}$ of each lamella and the third step the $Q_{ij}$ properties are determined in the main directions. With the coordinates of each lamella the properties $A_{ii}$, $B_{ij}$ and $D_{ij}$ can be calculated. The following step is to invert the matrix to the compliance matrix. With this matrix the equivalent elastic properties of the laminate can be calculated with the following equations: [7]

For the membrane stiffness:

\[
E_x = \frac{1}{h a_{11}} \\
E_y = \frac{1}{h a_{22}} \\
G_{xy} = \frac{1}{h a_{66}} \\
\nu_{xy} = -\frac{a_{12}}{a_{11}} \\
\nu_{yx} = -\frac{a_{11}}{a_{22}}
\]

(7-1)

For the bending stiffness:
\[
E_x = \frac{12}{h^2 d_{11}} \\
E_y = \frac{12}{h^2 d_{22}} \\
G_{xy} = \frac{12}{h^2 d_{66}} \\
\nu_{xy} = \frac{d_{12}}{d_{11}} \\
\nu_{yx} = \frac{d_{12}}{d_{22}}
\]

(7-2)

**Figure 36: Flow chart for calculation of laminate stiffness and equivalent elastic properties** [7]

With these parameters the FEA can be made. Figure 37 gives a design cycle for composite materials. In the FEA a failure analysis has to be done. Now a feedback can be made on the material design, parameters can be changed and the FEA needs to be changed with the new material properties. This process goes through, until the final design is reached. [6]
Figure 37: Design cycle for composite materials [6]
8 Joints

8.1 Introduction

In almost every construction there are joints required. Joints are required because of limitations of the material size, transportation of the product or to link sub-assemblies. Composite joints have a lot of similarity with joints for metals. Mechanical bondings are applicable for composites. Welding is applicable for thermoplastics, but this is still not well developed to use for full-load caring joints. An extra possibility is the use of adhesive bonding.[6] The connection of FRP materials can be more difficult than other materials, cause of their anisotropy. So it is crucial to connect elements on an appropriate way. The choice of the kind of connection depends on the sensitivity to UV radiation, temperature behaviour, mechanical properties and the influences of chemicals. [14]

The main types of connections of FRP element are the bonded connections and the mechanical bondings. Also a combination of a bonded and mechanical joint is possible.

![Joint Configurations](image)

*Figure 38: Overview joint configurations [6]*

Figure 38 gives an overview of different bonded joint configurations. The simplest joint is the single-lap joint. The strap joints looks for a large part on the single-lap joint.
In figure 39 the load distribution in a single lap joint is given. The load has to transfer from part B over part C to part A. Due to the load, the adhesive will be loaded in shear. The line of action of the resultant load is not in the neutral axis. This gives some bending actions in the joint. So the joint tend to peel apart. This mechanism is here displayed for a single lap joint, but this mechanism will occur in some extend in all joints. In these joints the ends are the critical parts, because there are highly loaded with a combination of shear and tension. [6]

8.2 Bonded connections
An adhesive connection consists of two parts that are joined with an adhesive. The most common adhesives are epoxy, acrylic and polyester. The choice of these adhesives is dependable of the used resin in the FRP elements. There are three main failure modes in adhesives connections; adhesive failure, cohesive failure or a combination of these. [14]

There are many advantages to use bonded joints instead of mechanical joints. The load is distributed over the adhesive area, which results in a uniform stress distribution. Glued joints can be more rigid and are more applicable to bond irregular surfaces. They are less expensive than mechanical joint and are used for aesthetic reasons. It is also possible to accommodate for differences due to temperature with an expansion joint between the joint materials. Glued joints have also a good response against dynamic loads. [14]

Some disadvantages glued connections are that working rules of these connections not fully developed. This makes a design more difficult and takes more time. Failure in glues joint is difficult to predict, because it takes suddenly place. Inspections of these joints are difficult when bonding is completed. [14]

The geometry of joint is an important factor for the joint strength. The most basic problems in a bonded joint is the shear stress concentrations or the peelstresses in the inherent and adherents. The maximum shear and peel stresses occur around the ends of the overlap. See figure 40 for an overview of these stresses it. In this figure the differences in strains and stresses is given for short and realistic overlaps. So it is clear that the lap joint needs to be long enough to resist creep deformations in the middle of the joint. [7]
The effects of the peel stresses that are induced by the eccentricity can be reduced with the following methods:

- Increasing the stiffness of the inherent
- Increasing length of the lap joint
- Tapering the of the adherents
- Using of adhesive fillets

These last two methods may give a significant increase of the load-bearing capacity of the joint. Due to these methods the stresses at the ends of the laps are reduced. This method is based on the increased flexibility of the joint ends and gives a better stress distribution in the overlap. Other improvements for the load bearing capacity can be achieved by using a stepped-lap or scarf joint. The stress configurations are reduced significantly in this configuration. [7]

**Surface preparation**

The preparation of the surfaces of the joint can influence the strength tremendously. So when the surfaces to be bonded are not in a suitable condition, the joint will have a low strength capacity.

When a bonded joint is made, it is important that all traces of contamination are removed. The following steps have to be carried out:

- Ensure that the composite is dry
- Prepare the area to be bonded with dry alumina grit
- Remove dust with water
- The bonding area needs to be clean
- Surface needs to be protected from contamination
- Adhesive needs to be attained at room temperature
- Bond soon after preparation, this is ideal in a facility with controlled humidity

[6]

### 8.3 Mechanical joints

Mechanical joints are based on the joints that are used in steel connections. Because of the earlier mentioned differences in material, there are some differences that have to be taken into account. Steel is an isotropic homogeneous material, while FRP are heterogeneous and anisotropic. Therefore each in continuity in the material reduces the load bearing capacity. [14]
One of the main advantages of mechanical joint is the well-known behaviour of these joints. There are several design codes about mechanical joint and every large manufacturer of FRP materials has their own guidance. The possible failure modes are illustrated in figure 41. Failure mode (a) shows the net section failure, this is caused primarily due to tensile stresses at the whole edge end. This occur when the ratio of by-pass to bearing load is high or when the ratio of hole diameter against plate width is high. Failure mode (b) shows a bearing failure, this can occur when the ratio \( d/w \) is low or when the by-pass load to bearing is low. Failure mode (c) shows a shear-out failure and occurs along shear-out plane of the whole section from the bolt to the edge. Failure mode (d) shows bolt shear failure and is caused by high shear stresses in the fastener. [7]

\[ d \]
\[ w \]
\[ (a) \]

\[ d \]
\[ w \]
\[ (b) \]

\[ d \]
\[ w \]
\[ e \]
\[ (c) \]

\[ (d) \]

Figure 41: Basic failure modes in bolted composite laminated [7]

### 8.4 Combined connections

The use of combining joint with bolt and glue can be interesting. When bolts are places on an appropriate way, they can prevent cracks which can lead to failure of a glued joint. Bolts will also provide pressure during the curing of the adhesive. The bolts are places as backup, so normally they are placed while they are not used. A joint need to be prepared for glue and also holes has to be drilled for the bolts. This give a hope extra work which is uneconomically. [14]

### 8.5 Comparison

Each method has its own advantages and disadvantages; these are summarized in table 9. There are no cuts out in bonded joints, so the fibres remain continuous and stress concentrations are reduced. Mechanical joint have the advantages that they can be disassembled and are easy to inspect. Further there is a lot of knowledge about mechanical joints. A combination can be made, but can give an inefficient joint.
<table>
<thead>
<tr>
<th>Mechanical connections</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- requires no special surface preparation</td>
<td>- low strength to stress concentrations</td>
</tr>
<tr>
<td></td>
<td>- can be disassembled</td>
<td>- special practices required in assembly</td>
</tr>
<tr>
<td></td>
<td>- ease of inspection</td>
<td>- fluid and weather tightness normally requires special gaskets or sealants</td>
</tr>
<tr>
<td>Bonded connections</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td></td>
<td>- high joint strength can be achieved</td>
<td>- cannot be disassembled</td>
</tr>
<tr>
<td></td>
<td>- low part count</td>
<td>- requires special surface preparation</td>
</tr>
<tr>
<td></td>
<td>- fluid and weather tightness</td>
<td>- difficulty of inspection</td>
</tr>
<tr>
<td></td>
<td>- potential corrosion problems are minimized</td>
<td>- temperature and high humidity can affect joint strength</td>
</tr>
<tr>
<td></td>
<td>- smooth external surfaces</td>
<td></td>
</tr>
<tr>
<td>Combined connections</td>
<td>Advantages</td>
<td>Disadvantages</td>
</tr>
<tr>
<td></td>
<td>- bolts provide support and pressure during assembly and curing</td>
<td>- structurally bolts act as backup elements – in an intact joint, bolts carry no load</td>
</tr>
<tr>
<td></td>
<td>- growth of bondline defects is hindered by bolts</td>
<td></td>
</tr>
</tbody>
</table>

*Table 9: Comparison different connections [7]*
9 Costs

This chapter will give an overview of the costs of a FRP material. First the costs of the different fibres will be mentioned, next to this the costs of the resin will be mentioned. In section 9.3 a range for the total costs of FRP in a construction are given.

9.1 Costs of the different types of fibres

Figure 42 gives a comparison of the costs of the different fibre types. These figures are calculated for a typical price for 300g of woven fabrics. The fibre prices in lightweight fabrics are considerably higher, due to the small bundle size. In unidirectional fabrics heavier bundles of fibres can be applied. This gives some difference in the cost comparison. The costs of fibres per kg are given in table 11. [28]

![Figure 42: Overview costs different fibre types, left: woven fabrics, right: unidirectional fabrics][28]

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Bulk Price Euro/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass</td>
<td>1,25-2,5</td>
</tr>
<tr>
<td>S-glass</td>
<td>15-20</td>
</tr>
<tr>
<td>Aramid</td>
<td>18-30</td>
</tr>
<tr>
<td>Carbon</td>
<td>10-45</td>
</tr>
</tbody>
</table>

*Table 10: Overview costs of different fibre types*

9.2 Cost of the resin

The most used types of resin are Polyester, vinyl ester and epoxies. Table 11 gives an overview of the costs of these materials.

<table>
<thead>
<tr>
<th>Resin type</th>
<th>Bulk Price Euro/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>1,30-2,55</td>
</tr>
<tr>
<td>Vinylester</td>
<td>2,55-5,10</td>
</tr>
<tr>
<td>Epoxies</td>
<td>3,80-19,50</td>
</tr>
</tbody>
</table>

*Table 11: Overview costs of the different resin types [28]*

9.3 Costs of a FRP construction

In the paragraphs before the raw material costs are mentioned. The costs of a construction consists of the material costs and the labour costs. The labour costs is dependable of the complexity of the construction. Next to this there are also extra material costs that are used during the production. This materials are like foil when the vacuum assisted resin injection is
used. So for the initial design the costs of a FRP construction can be given in a range. In consultation with the Dutch FRP manufacturer Fibercore a range for the costs for a glass fibre - polyester product is given of 4-7 €/kg, where the material costs are around the 2 €/kg. With this range the prices for products with other composition are determined with the base material costs of the previous parts. The amount of fibres and resin are estimated on 65%/35%. The labour costs are estimated to be equal for each composition. Due to the different density of the fibres, the labour costs per kg are adapted. See table 12 for a range of estimations for the construction costs.

<table>
<thead>
<tr>
<th>(fibre/resin)</th>
<th>Material costs range (€/kg)</th>
<th>Mean material base cost (€/kg)</th>
<th>Labour costs (€/kg)</th>
<th>Total costs (€/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass/polyester</td>
<td>1,3 - 2,5</td>
<td>1,9</td>
<td>2 - 5</td>
<td>4 - 7</td>
</tr>
<tr>
<td>E-glass/vinylester</td>
<td>1,7 - 3,4</td>
<td>2,6</td>
<td>2 - 5</td>
<td>5 - 8</td>
</tr>
<tr>
<td>E-glass/epoxie</td>
<td>2,1 - 8,5</td>
<td>5,3</td>
<td>2 - 5</td>
<td>7 - 10</td>
</tr>
<tr>
<td>S-glass/polyester</td>
<td>10,2 - 13,9</td>
<td>12,0</td>
<td>2 - 5</td>
<td>14 - 17</td>
</tr>
<tr>
<td>S-glass/vinylester</td>
<td>10,6 - 14,8</td>
<td>12,7</td>
<td>2 - 5</td>
<td>15 - 18</td>
</tr>
<tr>
<td>S-glass/epoxie</td>
<td>11,1 - 19,8</td>
<td>15,5</td>
<td>2 - 5</td>
<td>17 - 20</td>
</tr>
<tr>
<td>Aramid/polyester</td>
<td>12,2 - 20,4</td>
<td>16,3</td>
<td>2,8 - 7</td>
<td>19 - 23</td>
</tr>
<tr>
<td>Aramid/vinylester</td>
<td>12,6 - 21,3</td>
<td>16,9</td>
<td>2,8 - 7</td>
<td>20 - 24</td>
</tr>
<tr>
<td>Aramid/epoxie</td>
<td>13,0 - 26,3</td>
<td>19,7</td>
<td>2,8 - 7</td>
<td>22 - 27</td>
</tr>
<tr>
<td>Carbon/polyester</td>
<td>7,0 - 30,1</td>
<td>18,5</td>
<td>2,5 - 6</td>
<td>21 - 25</td>
</tr>
<tr>
<td>Carbon/vinylester</td>
<td>7,4 - 31,0</td>
<td>19,2</td>
<td>2,5 - 6</td>
<td>22 - 25</td>
</tr>
<tr>
<td>Carbon/epoxie</td>
<td>7,8 - 36,1</td>
<td>22,0</td>
<td>2,5 - 6</td>
<td>24 - 28</td>
</tr>
</tbody>
</table>

Table 12: Overview construction costs
10 Conclusion

In the literature study a introduction with the material FRP is given. The applications of FRP are summarized, the built up and manufacturing processes are given and the calculations methods to estimate the material properties. From this a conclusion can be made for the application of FRP in the following phase; the case study.

The laminate of a FRP consists of a stacking of lamellas. These lamellas are placed with the main fibre in different directions. This gives over the height different material properties, so the stresses varies over the height. So to check the structure on failure, a strain criterion is easier to apply. The stacking of the lamellas can give coupling effect between moments and normal forces. This problem can be solved by stacking the laminate symmetric.

The material properties can be determined according the CUR recommendation 96. With these lamella properties the laminate properties can be calculated with the classic laminate theory.

There are many manufacturing processes mentioned. For the case study a gate with a span of 49,3m will be investigated. To come with a economically solution, a manufacturing method should be chosen with a low production and equipment costs. The choice of the fibre and resin has a lot of influence on the costs of the structure. So for the case study there needs to be looked to the required material properties and the costs of the base materials.
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